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AERONAUTIC INSTRUMENTS
SECTION IV

DIRECTION INSTRUMENTS

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AERONAUTIC INSTRUMENTS
SECTION IV

DIRECTION INSTRUMENTS

IN FOUR PARTS

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REPORT No. 128.

DIRECTION INSTRUMENTS.

PART I.

INCLINOMETERS AND BANKING INDICATORS.

By W. S. Franklin and M. H. Stillman.

INTRODUCTION.

This report is Section IV of a series of reports on aeronautic instruments (Technical Reports Nos. 125 to 132 inclusive) prepared by the Aeronautic Instruments Section of the Bureau of Standards under research authorizations formulated and recommended by the subcommittee on aerodynamics and approved by the National Advisory Committee for Aeronautics. Much of the material contained in this report was made available through the cooperation of the War and Navy Departments.

SUMMARY.

This part points out the adequacy of a consideration of the steady state of gyroscopic motion as a basis for the discussion of displacements of a gyroscope mounted on an airplane, and develops the simple theory on this basis.

The principal types of gyroscopic inclinometers and stabilizers are briefly described and performance requirements stated. Experimental results are given for two of the spinning top inclinometers investigated.

The various liquid and mechanical inclinometers are then described, including new developments, and the chief characteristics to be determined by laboratory tests are discussed.

Part I concludes with a brief account of the possibilities offered by the earth inductor and other methods for the measurement of aircraft inclination without gyroscopes.

1. PRINCIPLES OF GYROSCOPIC INCLINOMETERS.

In the following discussion the normal position of the gyro axis is assumed to be vertical, and the terms *true zenith, pendulum zenith,* and *gyro zenith* refer respectively to the points on the celestial sphere where the true vertical cuts the sphere, where a pendulum would cut the sphere, and where the gyro axis cuts the sphere.

The utility of the gyroscope as an inclinometer or stabilizer is due to the fact that a very considerable torque must act on a spinning gyro for a considerable time to produce an appreciable displacement of the gyro axis from its normal position.

Proposition (*the steady state*).—The effect of any torque on an airplane gyro may be determined with sufficient accuracy for all practical purposes without considering the delay in the establishment of the steady precession corresponding to the torque, or, in other words, by assuming that the gyro is at all times in what is called the steady state. This proposition is of great importance, and it is valid chiefly because the precession is always very slow, not because the disturbing torques change slowly.

Righting torque.—In every case, what we will call a "righting torque" must be provided for to bring the gyro axis back to its normal direction after it has been displaced therefrom. This righting torque causes the gyro zenith to precess toward the pendulum zenith, and it is in general

a definite function[1] of the angle ϕ between the gyro zenith and the pendulum zenith. Under these conditions the "righting torque" carries the gyro zenith away from the true zenith while the pendulum zenith is displaced during a bank. Righting torque is due to pivot friction in the case of the simple spinning top, and in the case of the gyro which is supported by and driven through a universal joint the righting torque is due in part to the rocking friction in the cross-pins of the universal joint and in part to the driving torque.

Gravity torque.—When the center of mass of the gyro is not coincident with the point of support, the force of gravity produces a torque action on the gyro when the gyro axis is inclined. This torque is neglected in the following discussion because the following discussion applies to a gyro which is always very nearly balanced and of which the axis of spin is always very nearly vertical.

Torque due to horizontal acceleration of the airplane. Centrifugal torque.—When the center of mass of the gyro is above or below the point of support the inertia reaction of the supported gyro causes a torque action about a horizontal axis when the airplane has a horizontal acceleration, and the expression for this torque action is well known.

Error of gyro zenith developed by the righting torque.—While the airplane is performing any maneuver the pendulum zenith describes a definite path on the celestial sphere and the righting torque causes the gyro zenith to follow the pendulum zenith in a curve of pursuit; that is to say, the gyro zenith is being carried toward the pendulum zenith at each instant by the righting torque at a rate which is easily expressed in terms of the righting torque and the angular momentum of the gyro. Therefore, if the righting torque is a known function of the angle ϕ between the gyro zenith and the pendulum zenith, it is evidently possible to calculate the movement of the gyro zenith during any specified movement of the pendulum zenith, using step-by-step integration. The following very simple case, however, covers the ground sufficiently for most practical purposes:

The gyro zenith G may be assumed to be always very near the true zenith Z as shown in Figs. 1 and 2. Then while the airplane is banking through any fraction of a circle, the pendulum zenith P will describe the same fraction of a circle PP' (a small circle on the celestial sphere) whose angular radius ϕ is the angular displacement of the pendulum due to centrifugal action in the banking airplane, and the gyro zenith G will describe approximately the same fraction GG' of a much smaller circle. In this statement the rate of precession p of the gyro is assumed to be constant, because ϕ is sensibly constant and consequently the righting torque which produces p is constant. It is evident, therefore, that the maximum displacement of the gyro zenith by the righting torque during banking will be produced by a half-circle bank, in which case PP' and GG' are semicircles as indicated in Fig. 2.

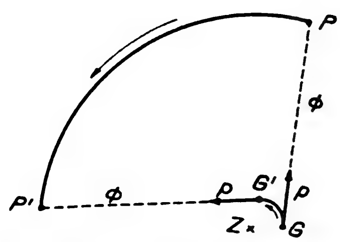

FIG. 1.—Effect of righting torque in displacing gyro zenith.

To calculate the displacement GG' of the gyro zenith which is produced by the righting torque during a half-circle bank of the airplane in a circle of radius R at velocity V, we must know, by test, the value of the righting torque which corresponds to the angle $\phi = \tan^{-1}\left(\frac{V^2}{Rg}\right)$. Let us represent this torque by T. Then the rate of precession p in Fig. 2 is $p = T/\omega K$, where ωK is the angular momentum of the spinning gyro. Multiplying p by the time of a half-circle bank, namely, $\pi R/V$, we get the length of the semicircle GG' in radians, and multiplying this by $2/\pi$ we get the arc GG' in radians. Therefore

$$\text{Displacement of gyro zenith by righting torque during a half-circle bank} = GG' = \frac{2TR}{\omega KV}$$

This calculation can be easily modified so as to give the displacement GG' in Fig. 1 due to bank in any fraction of a circle.

[1] In the Gray gyro the righting torque can be reduced to zero at any time, whatever the value of ϕ may be, and to this extent the righting torque in the Gray gyro is not a definite function of ϕ.

It must be remembered that the above equation is an approximate equation and is true only when the displacement GG' is small. In particular GG' does not increase indefinitely with R as the equation would seem to indicate. In fact, if we assume the righting torque to remain finite when ϕ is very small, the gyro zenith would catch up and remain coincident with the pendulum zenith if the radius of the banking circle is so large that the speed of the pendulum zenith along the semicircle PP' is less than the speed of the gyro zenith p.

In many cases the righting torque is pretty nearly independent of ϕ, as, for example, in the gyro which is supported and driven by a universal joint. In such a case the rate of travel p is nearly independent of ϕ and the maximum displacement GG' in Fig. 2 depends only on the time required for the semicircular bank and is proportional thereto.

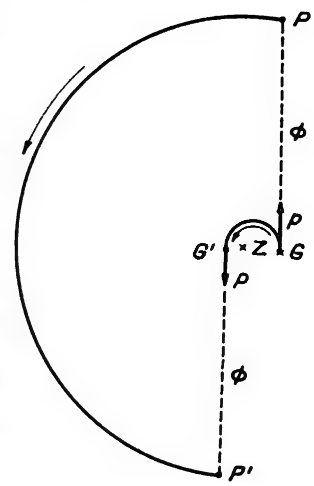

FIG. 2.—Maximum displacement of gyro zenith by righting torque.

Error of gyro zenith developed by centrifugal torque.—Here again the gyro zenith travels in a kind of curve of pursuit as the pendulum zenith describes a curve on the celestial sphere, but with this difference, namely, that G travels at each instant in a direction at right angles to the line GP (see Fig. 3). In this case also the total displacement of the gyro zenith during any prescribed maneuver could be found by stepwise integration, but the following very simple case covers the ground sufficiently for most practical purposes.

During a half-circle bank of the airplane the pendulum zenith traces the semicircle PP' (Fig. 3), whose radius is the banking angle ϕ. To calculate the displacement GG' of the gyro zenith in Fig. 3, we calculate the value of the centrifugal torque, namely $\frac{V^2}{R}\cdot mx$, where V is the velocity of the airplane, R is the radius of the banking circle, m is the mass of the gyro and stabilized structure and x is the distance of the center of mass of gyro and stabilized structure above or below the point of support. When gyro and stablilized structure are mounted separately and linked together this torque is the algebraic sum of the centrifugal torques exerted on them individually. Dividing this torque by ωK we get the rate of precession p; multiply p by the time of the half-circle bank we get the length of the semicircle GG' in radians; and multiplying this by $2/\pi$ we get the diameter GG' in radians. Therefore

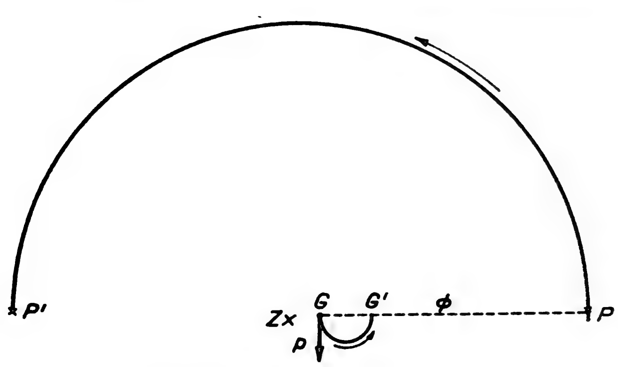

FIG. 3.—Effect of centrifugal torque.

$$\text{Displacement of gyro axis by centrifugal torque during a half-circle bank} = GG' = \frac{2\,Vmx}{\omega K}$$

This calculation can be easily modified so as to give the displacement of the gyro axis by centrifugal torque during a bank in any fraction of a circle.

It is to be noted that the displacement of gyro zenith by righting torque during a half-circle bank is always in the direction in which the airplane travels before the bank, as may be seen from Fig. 2; whereas the displacement of the gyro zenith by centrifugal torque during a half-circle bank is to right or left with reference to direction of travel of the airplane before the bank. Fig. 3 shows the displacement to the right. The displacement of gyro zenith by the combined action of righting torque and centrifugal torque is to be found by superposition, and it is numerically equal to the square root of the sum of the squares of the separate displacements.

The displacement of gyro zenith at starting of an airplane is very similar to displacement by centrifugal action. It may be either to right or left with reference to the pilot.

Proposition (stability of gyro zenith).—Leaving out of account, for the moment, the effects of centrifugal torque and the effects of the earth's rotation, it may be stated that the utmost degree of stability (fixity) of gyro zenith depends solely upon smallness of righting torque (smallness of speed of pursuit p in Figs. 1 and 2). The slower the speed of pursuit the less the gyro zenith will ever depart from the mean position of the pendulum zenith.

Therefore the design of a gyro to give a fixed zenith to any desired degree of accuracy depends upon the reduction of centrifugal torque, and it is bound up with the question of the rotation of the earth, and the latter, only, is serious because the centrifugal torque can be practically eliminated by careful balancing of the gyro and stabilized structure.

Influence of earth's rotation.—The true zenith travels to the east at 45° North latitude at a speed of about 10° per hour, and a stable-zenith gyro must follow the true zenith with negligible lag.

Ordinarily the righting torque is the only thing available for carrying the gyro zenith forward with the true zenith, and, if the righting torque is a vanishing function of ϕ (becoming zero when the angle ϕ is zero) we face a dilemma, either (*a*) enough lag must be allowed to develop to give a righting torque sufficient to carry the gyro zenith forward at a speed of 10° per hour, or (*b*) the righting torque corresponding to a very small value of ϕ must be large enough to carry the gyro zenith forward. In the first case a very large zenith error will soon develop due to the earth's rotation, and in the latter case very large displacements of gyro zenith will be produced by the righting torque during a maneuver of the airplane (see Figs. 1 and 2). Under conceivable conditions the lag error under case *a* might be sufficiently constant to be allowed for as a correction; but, in the second case, no allowance correction would be possible because irregular flight is unavoidable. This dilemma does not arise in the case of the gyro which is supported upon and driven by a universal joint *if the gyro is mounted on a nonoscillating base* as pointed out in Part II of this report because the righting torque of this gyro is *not* a vanishing function of ϕ, and because the nearly constant value of the righting torque in this gyro may be sufficient to carry the gyro zenith forward 10° per hour and yet be small enough to displace gyro zenith only a small fraction of a degree in a short-radius bank. This valuable characteristic of this gyro disappears, however, when it is mounted on an oscillating base as it must be on an airplane or on board ship. Therefore in practice we must design a gyro so that its lag behind the earth's rotation will be constant, or we must compensate for the earth's rotation, and the former is undoubtedly impracticable.

Compensation for the earth's rotation.—To compensate for the earth's rotation is to provide a constant torque which acts on the gyro about an east-west axis, and thus carries the gyro zenith eastward (by precession) at a constant angular speed, with arrangements for adjusting this torque or altering the speed of revolution of the gyro. This adjustment is necessary not only to adapt the compensation for a given latitude but also to change the compensation for change of latitude. To provide for a torque about an east-west axis means, of course, a compass of some kind to define the east-west direction.

Very simple considerations lead to the conclusion that no single combination of gyros can be devised which will inherently compensate for the earth's rotation, for, in the first place, any gyro or combination of gyros must have a very considerable resultant angular momentum if the gyro or system of gyros is to be displaced to a negligible extent by unavoidable disturbing torques, and in the second place a gyro or system of gyros with a large resultant angular momentum must be acted on by an outside torque about an east-west axis to make the momentum axis follow the plumb line.

Hand-controlled compensation.—If a gyro stabilizer is to be used for bomb sights on a large airplane one of the crew could, during the major part of the journey to the objective, devote himself to a hand-controlled compensator for the gyro stabilizer, and be relieved for other duty very shortly before the bomb dropping is to be done. It is very easy to provide a torque of the correct value by hanging a weight on an arm attached to the stabilized structure so as to give the desired gravity torque, and the helper could watch a good magnetic compass and keep this arm north or south. If the arm could be thus held so that its mean position is within 1° of

geographical north or south, then about 59/60 of the effect of the earth's rotation would be compensated. It might seem that under the specified conditions all but about 1/5000 of the effect of the earth's rotation would be compensated, but the lack of complete compensation would show itself as a northward or southward displacement of the gyro zenith.

Automatic compensation.—On board a ship which is equipped with a gyro master-compass the turning of the above-mentioned arm could be done automatically.

Displacement of gyro zenith due to rolling and pitching oscillations of the airplane.—An approximate calculation of these displacements is very easy and, no doubt, sufficiently accurate for all practical purposes inasmuch as this calculation would be always made to show that these displacements would be negligible

Of course rolling and pitching oscillations involve certain amounts of fore-and-aft and athwartship accelerations, and therefore lead to disturbing torques when the center of mass of the stabilized structure is above or below the point of support. The effects of these torques are, however, negligible if the stabilized structure has been balanced with moderate care.

The chief displacement of the gyro zenith due to pitching or rolling oscillations is that which grows out of the righting torque, and a very rough but really adequate calculation of this displacement may be made as in the following example. Suppose that the half-period of the rolling oscillations is t seconds, and that the half-amplitude is $a°$. Knowing the value of the righting torque for $\phi = a°$, we may assume that this value of righting torque acts constantly but in reverse directions during successive half-oscillations. Then the range of the to and fro movement (athwartship) of the gyro zenith must be less than the product pt, where p is the precession rate corresponding to the above-mentioned value of righting torque.

2. BEHAVIOR OF A SPINNING TOP ON AN AIRPLANE.

On account of the popularity of the spinning top inclinometer with the French Air Service, the question of its adoption for American production came up and led to a detailed study of the behavior of a spinning top in an airplane.

The complete formulation of the motion of a spinning top on an airplane is complicated by two effects which are ordinarily negligible, as follows:

1. When a force acts on a body the acceleration which corresponds to the force begins simultaneously with the force without any time lag, and when the force ceases the acceleration ceases. There is no momentum effect associated with translatory acceleration. On the other hand, when a torque acts on a spinning top or gyro, axis of torque not parallel to axis of already existing spin, the angular acceleration which is produced shows itself as a precession, there is a certain amount of angular momentum associated with this precession, and therefore some time is required for a precession to be established after a torque begins to act, and a precession does not cease instantly when the torque ceases. This lag effect is neglected in the following discussion. After the precession corresponding to a given torque is fully established we have what is called *steady gyroscopic motion,* and to neglect the above lag effect is to assume that the motion of the gyroscope or top is always in a steady state.

2. A spinning top which is inclined is nonsymmetrical with respect to the vertical axis of precession, and the precessional motion develops what may be thought of as a torque reaction which very greatly complicates the equations of motion of a precessing top. This effect is neglected in the following discussion.

As a matter of fact effects 1 and 2 are negligibly small when the rate of precession is very slow, and the precession of any well-balanced gyro or top is always very slow.

Other approximations are used in the following discussion but they refer so particularly to the arrangement of the spinning top that they are best explained after the arrangement of the top and the details of our notation are specified.

Figure 4 is a top view of the cup jewel showing the pivot of the top, and the vector ω represents, according to the usual conventions, the angular velocity of the top.

Figure 5 is a side view of the cup jewel and pivot as seen by looking in the direction of the arrow A in figure 4.

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Figure 6 is a side view of the cup jewel and pivot as seen by looking in the direction of the arrow B in figure 4.

The vertex V of the cup jewel is the lowest point in the cup with respect to the pendulum vertical.

Notation.—The *top zenith* is the point where the axis of the spinning top cuts the celestial sphere.

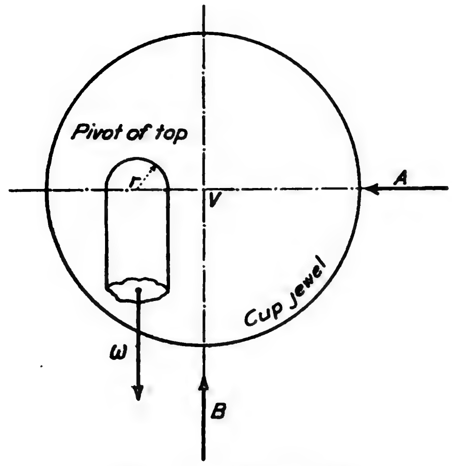

FIG. 4.—Top view of cup jewel.

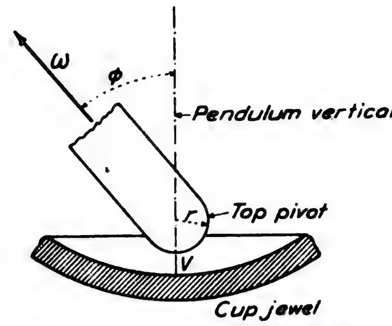

FIG. 5.—Side view—looking along A of figure 4.

The *pendulum zenith* is the point where a non-oscillating pendulum mounted on the air plane would cut the celestial sphere.

ϕ = angle between pendulum zenith and top zenith.

β = angle whose tangent is equal to μ, where μ is the coefficient of sliding friction between top pivot and cup jewel.

r = radius of the spherical end of the top pivot.

m = mass of the top.

K = moment of inertia of the top.

ω = speed of top in radians per second.

g = acceleration of gravity.

a = horizonal acceleration of the air plane.

$G = \sqrt{g^2 + a^2}$

3. Occasionally the spherical end of the pivot of the spinning top rolls round and round in the jewel cup and carries the center of mass of the top rapidly around a small circular path but this condition seems to be abnormal—it occurs when the top is suddenly disturbed, and it lasts for a short time only. This motion is therefore negligible; or, at any rate, it is neglected in this discussion.

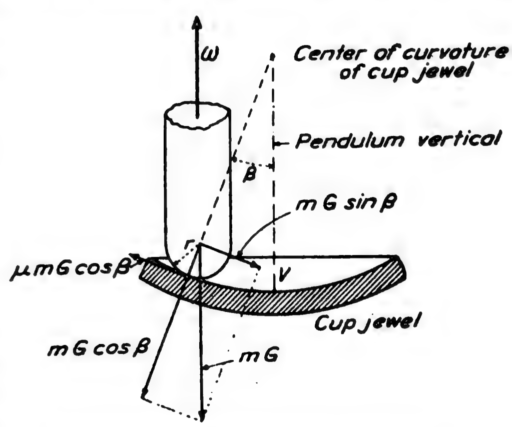

FIG. 6.—Side view—looking along B of figure 4.

4. The pivot of the inclined top rolls sidewise in the cup jewel until the down-hill component $mG \sin \beta$ in figure 6 is balanced by the up-hill frictional force $\mu mG \cos \beta$. This relation involves two approximations, namely, (*a*) The center of mass of the top travels very slowly in a very small path so that the acceleration of the center of mass of the top relative to the cup jewel is negligible and therefore the forces which act on the top are balanced. The horizontal acceleration of the airplane is not neglected in this statement because everything is referred to the pendulum vertical; and (*b*) the slow-speed sliding of the pivot in the cup jewel due to the slow motion

of the pivot in the cup as the top precesses is negligible in comparison with the high-speed sliding $\omega r \sin \phi$ which is due to the spinning motion of the top.

Righting torque.—The two equal and opposite forces $mG \sin \beta$ and $\mu mG \cos \beta$ in figure 6 constitute a pure torque whose value is $\mu mGr \cos \beta$ and whose component at right angles to the axis of spin of the top is $\mu mGr \cos \beta \cos \phi$. This is the righting torque which causes the top zenith to move towards the pendulum zenith. The value of the righting torque is given with sufficient accuracy for most purposes by taking $G = g$, $\cos \beta = 1$ and $\cos \varphi = 1$ which gives the value μmgr for the righting torque.

Motion of top zenith due to righting torque.—This motion may be calculated for any given maneuver of the airplane, or the displacement of the top zenith during any fraction of a circular bank of the airplane can be calculated as explained in section 1 (Principles of Gyroscopic Inclinometers).

Motion of top zenith due to centrifugal torque.—When the center of mass of the top is above or below its point of support a horizontal acceleration of the airplane causes a torque action on the top and this torque action is called centrifugal torque in section 1. The motion of the top zenith due to centrifugal torque can be calculated for any given maneuver of the airplane, or the displacement of the top zenith during any fraction of a circular bank of the airplane can be calculated as explained in section 1 of this paper.

3. DESCRIPTION OF SPECIFIC INSTRUMENTS.

SPINNING TOPS.

Garnier.—One of the best known spinning tops is a French type, the Garnier, shown in figure 7. This consists of an air-driven rotor, weight about half a pound, spinning with its

FIG. 7.—Garnier spinning top.

steel pivot in a hemispherical steel cup. The casing is covered by a glass dome graduated in zones and great circles to show angles relative to the vertical. A white spot on the top of the spindle, made self-luminous for observations at night, constitutes the indicating element, and moves about just underneath the surface of the convex dome. This top is driven by air jets like a turbine, having the appropriate blades in the form of grooves on the rotor. The air jets are actuated by suction inside the case generated by a Venturi tube mounted outside the fuselage in the air stream.

A characteristic source of error in this design is the disturbing torque produced by the air jets whenever the axis of rotation is displaced from the axis of symmetry of the casing.

Hebrard.—This instrument, also of French construction, is somewhat similar to the Garnier, but larger, more substantially constructed, having a slightly greater range of angular deflection, and driven in a different manner. Instead of having an air-drive, the Hebrard instrument is

mechanically driven through a universal joint in the bottom of the casing by means of a flexible shaft connected to an air propeller outside of the fuselage. The connection between this universal joint and the rotor itself is made through a ratchet, which permits the top to spin even if the propeller should stop. The antivibration mountings of the two instruments are also different, the Hebrard mounting consisting of three rubber disks,clearly shown in figure 8.

Construction and performance constants for the Hebrard top are given below in section 5 (experimental results).

Other top developments.—Two modifications of the spinning top suggested by one of the authors in the course of this work were, first, what may be termed a breathing top, and, second, a top spinning in hydrogen at extremely low pressure.

The breathing top is a hollow top mounted on a pivot in a glass casing. The air pressure in this casing is subjected to periodic increase and decrease, an inlet valve admits air to the interior of the top when the pressure increases, and the air thus entrapped escapes through a series of nozzles and drives the top by reaction.

The idea of the hydrogen top was to provide so small a resisting torque as to enable the top to run for several hours after being started at the beginning of a flight. This would have the advantage that the driving apparatus would not be available to the enemy in the event of a crash, and also that it would simplify the apparatus needed on the airplane. Laboratory data on the experimental model of this type will be found in the section on experimental results.

FIG. 8.—Hebrard spinning top.

INCLINOMETERS WITH PENDULOUS GYROSCOPES.

Sperry inclinometer.—The possibilities of a single gyrostat supported in gimbals, with its axis vertical, driven by three-phase current through flexible leads and slip rings, have been developed by the Sperry Gyroscope Co., and modifications of this arrangement have also been constructed by the Royal Aircraft Establishment. Such inclinometers are satisfactory for steady flight, but subject to disturbances from acceleration, since the center of gravity must be placed below the point of support in order to utilize gravity for the righting torque. This disturbance is, however, far less than in the case of an ordinary pendulum. Hence the utility of the instrument. In this type of gyroscope the gravity torque is not in itself a righting torque, but it produces precession and thereby causes the gimbal axes to rock and the friction which opposes this rocking motion is a righting torque.

Multiple gyro instruments.—Undoubtedly the best known example of this type is to be found in the Sperry automatic pilot, with its four gyro units. A self-recording inclinometer, known as the Bureau of Standards stable zenith, was developed by Prof. J. F. Hayford and Dr. L. J. Briggs for use in free flight tests by the National Advisory Committee for Aeronautics; this is briefly described in the annual report of the Director of the Bureau of Standards for 1918 (p. 128) as a two-gyro combination. The use of coupled gyros for stabilization has been discussed by one of the present authors in a paper on Gyroscopic Oscillations (Phys. Rev. 34: 48–52, 1912).

INCLINOMETERS WITH NEUTRAL GYROSCOPES.

The possibilities of the neutral or free gyro have never been fully utilized in practice because of mechanical difficulties. A neutral gyro uninfluenced by external force, would maintain its axis of rotation fixed in space. Two instruments in which this principle has been sufficiently realized for temporary observations are the Norton recording stunt indicator and the Duff-Hyde stabilizer. The new type of gyro stabilizer described in Part II of this report is also neutral in the sense of having its center of mass at the effective point of support, but it is not isolated from the action of external forces, because it obtains the necessary righting tongue from the rocking friction of a universal joint.

Duff-Hyde.—The stabilizer (or inclinometer) developed by Prof. A. W. Duff and Lieut. W. A. Hyde [2] is shown in figure 9. It is a short period gravity pendulum, combined with an independently supported gyrostat. The oscillations of the pendulum are damped by air dash-pots, and the pistons of these dashpots serve for the coupling between the pendulum and the gyroscope. The pendulum part is mounted on gimbals, so as to be free to move about two horizontal axes aa and bb at right angles. The gyro itself is of the Sperry A. C. motor type. It is mounted above the pendulum with its axis vertical, and on gimbals having two horizontal axes of rotation respectively parallel to aa and bb. Four dash pots and their pistons form links between the pendulum and the gyro. The mechanical connections are made by hinged joints. Now the axis of the spinning gyro tends to remain fixed in space and so furnishes a comparatively stationary position for the dash-pot pistons. The effect of this device is to damp the quick oscillations of the pendulum, but to permit slow movements without much hindrance, thus enabling the pendulum to maintain the vertical. The stable zenith of this instrument is through the pendulum itself.

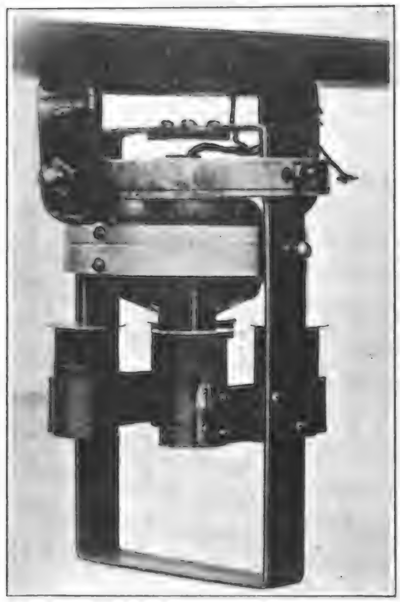

FIG. 9.—Duff-Hyde stabilizer.

Norton.—The recording inclinometer or stunt indicator under development by F. H. Norton, of the National Advisory Committee for Aeronautics, differs from ordinary Gimbal instruments in that no obstacle is encountered when a complete rotation takes place, as in looping the loop. In other instruments when two of the axes become coincident, the instrument loses its freedom, it is then locked and no longer able to rotate about the third axis. The Norton gyro is wholly incased inside of a spherical shell. This shell is gripped between four rollers, symmetrically placed at the corners of a regular tetrahedron. These are like planimeter wheels in that they record the motion in one direction, while slipping freely at right angles. These wheels in turn are geared to the dials after the fashion of a polar planimeter, so as to show at a glance the total components of rotation of the aircraft about the respective three axes.

An instrument developed by the Royal Aircraft Establishment, for use in aircraft stability investigations, has somewhat the same purpose, but records angular velocity instead of angular displacement. The principle of operation of the Royal Aircraft Establishment instrument is similar to that of a gyro turn indicator.

STABILIZERS FOR BOMBING AND PHOTOGRAPHY.

Two further instruments particularly designed as stabilizers are the Gray and Lucian instruments; each carries a single gyro unit of the pendulous type, and in each the auxiliary device for producing a righting torque is unique. Attention may here be called to Report No. 131, in which is given a more detailed account of a proposed type of stabilizer with a particularly simple erecting device—namely, the friction of a universal joint, upon which the gyro is sup-

[2] Aviation and Aircraft Journ., I: 322, 1920.

ported, and through which it is driven. Such stabilizers may prove useful for a variety of purposes, including not only bomb sighting and photography, but the control of a double-pivot compass so as to eliminate the northerly turning error; the furnishing of an artificial horizon for sextant observations; and the mounting of dynamical type ground speed or distance indicators, which have to be held horizontal.

Gray.—The stabilizer developed by Dr. J. G. Gray in Scotland obtains its restoring torque by the displacement of a number of balls which are slowly rolled around a horizontal plate by means of a pair of rotating crossbars. When this plate is inclined, a restoring torque of the desired direction is produced on the vertical spinning gyro which is rigidly attached to the horizontal plate. This ingenious arrangement is effective because of the fact that the ball is guided into a sidewise displacement by the rotating arms instead of rolling directly forward when the airplane pitches downward. Also the restoring forces may be easily made inoperative at will so as to preserve the position of the gyroscope during a rapid bank.

Lucian.—The stabilizer developed by Dr. A. N. Lucian [3] utilizes electromagnetic action for the production of a suitable righting torque. This torque is brought into play when either of two simple pendulums, of short period, is displaced so as to make an electric contact. These pendulums swing about the gimbal axes of the gyro, one in a fore-and-aft plane, the other transversely. The entire construction of this outfit is comparatively light, as stabilizers go.

4. TESTING OF ANY PROPOSED TYPE OF GYRO INCLINOMETER OR STABILIZER.

The only thing that need be said here concerning the driving mechanism is that it is necessary to determine whether this mechanism exerts any torque on the gyro about an axis at right angles to the axis of spin, and if so how much. For example, the gyro which is supported on and driven through a universal joint has such a torque exerted on it as set forth in Part IV–B.

Moment of inertia and normal running speed of gyro must be determined.

Mass and location of center of mass of gyro and stabilized structure must be determined for the purpose of calculating what is above called the gravity torque and for calculating torque action due to horizontal acceleration.

The most important thing to determine is the experimental functional relation between righting torque and angle ϕ between gyro zenith and pendulum zenith. This determination can be easily made by observing the rate p at which the gyro zenith approaches the pendulum zenith for various values of ϕ, speed of gyro and moment of inertia of gyro being known. This test would of course be made in the laboratory and the pendulum zenith would coincide with the true zenith. In this test the gyro zenith should be displaced northwards or southwards of the true zenith so as to eliminate the influence of the earth's rotation.

A separate test of the amount of lag of gyro zenith due to the earth's rotation might be advisable, although this can be calculated from the above data.

The most important calculations from these test data would be:

(*a*) Displacement of gyro zenith due to a half-circle bank of the airplane, using several airplane velocities and several radii of banking circle.

(*b*) Displacement of gyro zenith due to centrifugal action on unbalanced stabilized structure during a half-circle bank at various airplane speeds. This displacement is independent of the radius of the banking circle.

(*c*) Lag of gyro zenith due to earth's rotation at a chosen latitude and for a specified amplitude and frequency of east-west oscillation of the pendulum zenith. In general this will require tedious step-by-step integration using a tabulated set of values of righting torque at short intervals during one oscillation of the pendulum zenith. An example of this calculation is given in Part IV–B.

(*d*) Upper limit of possible displacement of gyro zenith during a prescribed rolling or pitching oscillation of the airplane.

Various other simple tests such as time required to bring gyro up to normal speed, time for gyro to come to rest when driving torque ceases, will suggest themselves to anyone.

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[3] C. E. Mendenhall: Journ. Franklin Inst. 191: p. 85. An air-jet type is also referred to here.

5. EXPERIMENTAL RESULTS.

Construction and Performance Constants of the Hebrard Top.—Mass = 596 grams; moment of inertia K = 7680 gr.-cm ^{2}; pivot of hardened steel, small radius r = 0.08 cm.; distance of center of mass below point of support, x_1 = 0.052 cm. Cup jewel of hardened steel, radius of curvature 0.41 centimeter. Staff of top 6.8 centimeter long, disk on end of staff 0.9 centimeter diameter. Inclination of staff with respect to casing can be read to about 1°.

When tried out on an airplane (Curtis J. N.) the behavior of the top was quite satisfactory for banking angles of less than 30°, but the driving mechanism is very bumpy when the casing is inclined 30° or more with respect to the top.

The top came to rest in 13 minutes from 1,000 revolutions per minute when the driving torque ceased. At 1,500 revolutions per minute the top rose from 20° inclination to 10° inclination in 35 seconds; calculated time 30 seconds; this test was made in the laboratory.

(1) Error developed in 15 seconds by horizontal component of driving torque when casing is inclined 20° (in the laboratory) was about 2°.

(2) Calculated error due to pivot friction alone, when V, the speed of the airplane = 36 meters per second, and R, the radius of the turn = 500 meters, with top running 1,500 revolutions per minute, is 4.7°.

(3) Calculated error due to horizontal acceleration alone, when V = 36 meters per second, R = 500 meters, and speed of top = 1,500 revolutions per minute, is 2.7°.

(4) Calculated error due to horizontal component of driving torque alone, when V = 36 meters per second, R = 500 meters and speed of top = 1,500 revolutions per minute, is 0.9°.

(5) Calculated error due to combined action of pivot friction, centrifugal force and horizontal component of the driving torque T when V = 36 meters per second, R = 500 meters and speed of top = 1,500 revolutions per minute, is 6.2°.

(6) Calculated value of constant error of staff of top due to rotation of the earth is 0.12° at 45° N. latitude, when speed of top is 1,500 revolutions per minute.

Data for hydrogen top.—Taking the mass of the top 100 grams, diameter 6 centimeters, thickness of rotor at edge 1 centimeter, the radius of gyration will be 2 centimeters and the moment of inertia 400 centimeter-gram-second units. These data apply to the top constructed at the Bureau of Standards by Mr. F. Cordero.

Tests made on the first model of this type, as actually constructed, showed that it would run about one hour in hydrogen at 2 or 3 millimeters pressure, while dropping its speed from 3,000 to 500 revolutions per minute.

6. DESCRIPTION OF LIQUID AND PENDULUM INCLINOMETERS.

For practically steady flight, free from acceleration, instruments constructed so as to show the direction of the apparent gravitational field are satisfactory and have been used with good results in performance testing of aircraft. Such instruments, of course, can not take the place of gyroscopic inclinometers for absolute measurement when accelerations are present. A forward acceleration equal to gravity, which is not uncommon, throws the direction of apparent gravitational force 45° toward the rear. Inclinometers constructed on the liquid or pendulum principle will, of course, respond to this change of direction almost instantly, and this effect is indistinguishable from a true inclination of 45°.

Fore-and-aft inclinometers, French types.—The principal type of liquid fore-and-aft inclinometer is triangular in shape, as shown by figure 10, and has been extensively developed by the French. The principle involved is simple enough: The liquid seeks its proper level, so when the airplane climbs the liquid recedes down the front part of the triangular circuit, allowing the meniscus to rise along the rear part of the circuit to which a graduated scale is attached. The commercial form is not over 10 inches on each side. It is understood that Capt. Toussaint has developed a special form of this instrument in which the triangular circuit extends back a long distance through the fuselage of the airplane in order to secure extremely high sensitivity.

Drexler.—A liquid fore-and-aft indicator of the triangular type forms a part of the Drexler combination inclinometer and gyro indicator described in Part III of this report.

Rieker.—This is an American-made instrument quite similar to the French types of fore-and-aft inclinometer.

National Advisory Committee for Aeronautics.—A liquid fore-and-aft inclinometer of exceptionally open scale was developed by Edward P. Warner of the National Advisory Committee for Aeronautics and employed with good results in free flight investigations.[4]

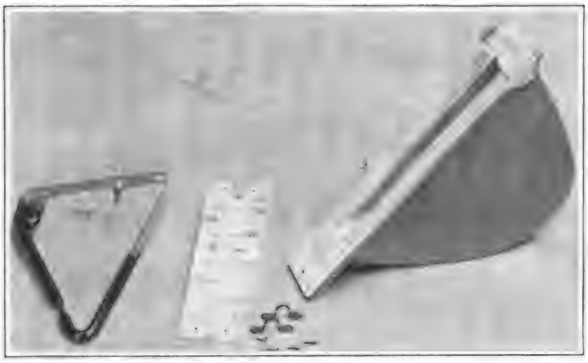

FIG. 10.—Liquid fore-and-aft inclinometer.

Danish sector type.—Liquid inclinometers of the sector type are familiar on German airplanes, and in steady flight may be used either for fore-and-aft or for lateral observations. Two such instruments of Danish manufacture are shown in figure 11.

German double circuit type.—A double circuit type of liquid inclinometer found on German aircraft is shown in figure 12. While similar in principle to the triangular circuit, this arrangement is evidently more sensitive for a given size and can therefore be furnished in a more compact form.

Sperry fore-and-aft inclinometer.—Figure 13 shows a liquid damped pendulum device for fore-and-aft observations developed by the Sperry Gyroscope Co.

Richard clinometer.—This instrument of French design, is similar to the Sperry in its fundamental principle.

Russell liquid-damped pendulum.—Pendulums damped with a viscous liquid have been employed primarily for artificial horizons in connection with sextant observations. Such an instrument, developed by H. N. Russell, is further described in Report No. 131. This problem has also been investigated by Mr. E. G. Fischer, of the United States Coast and Geodetic Survey.

Pentz compass.—This compass, considerably used by the United States Air Mail Service, was designed to serve also as an inclinometer. From the description given in Part III of this report it will be noticed that the pendulum zenith at any time is indicated by looking down through the spherical glass cover, which is suitably marked.

FIG. 11.—Liquid inclinometers, sector type.

7. BANKING INDICATORS.

Banking indicators are, of course, intended only to show the departure of the airplane from the proper banking angle. It is a fallacy to suppose that a banking indicator ought to show the absolute inclination of the craft with respect to the earth, which it can not do for the reasons explained at the beginning of section 6. The instrument is not designed to show absolute inclination. The indicator should read zero when the banking angle is correct for the actual speed and radius of turn, regardless of the absolute amount of the bank relative to the horizontal.

British bubble type.—Figure 14 shows the familiar bubble type of banking indicator developed by the British. The Taylor and Rieker instruments of American manufacture are based evidently on the same principle. The banking indicator is mounted transversely on the instrument board in front of the pilot. For night flying the bubble can be illuminated by a small electric lamp placed at the end of the glass tube so that the rays are transmitted through the liquid.

[4] Report No. 70, National Advisory Committee for Aeronautics, Fifth Annual Report.

The bubble banking indicator is sometimes furnished in combination with the fore-and-aft inclinometer.

Bubble banking indicators appear to have been very popular among the British fliers and in the American Navy, but not among the French or in the American Army.

Sperry pendulum type.—In figure 15 is shown an air-damped pendulum indicator developed by the Sperry Co. This is made in a self-luminous form for use at night. The zero position is that in which the movable indicator is horizontal.

Luminous rolling ball type.—In figure 16 is shown the luminous ball banking indicator developed by one of the authors and found satisfactory for night flying. It operates essentially on the same principle as a bubble banking indicator, but deflects in the opposite direction.

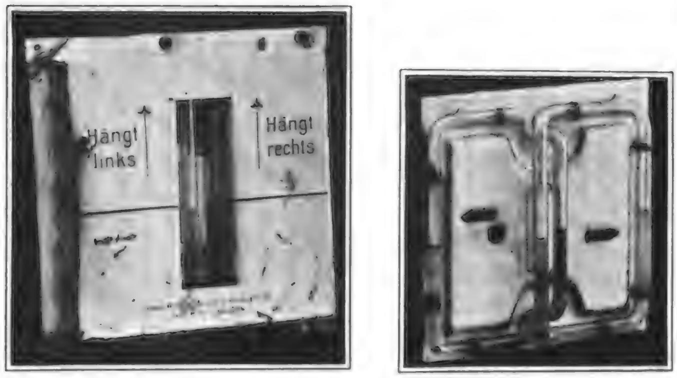

FIG. 12.—Liquid inclinometer—Double-circuit type.

Drexler.—In the new model Drexler aircraft steering gage, to be described in Report No. 131, another form of rolling ball banking indicator is employed, having a steel ball. The action of this instrument is similar to the one previously developed at the bureau, but does not have the self-luminous feature.

8. PERFORMANCE CHARACTERISTICS OF THE LIQUID AND PENDULUM TYPES.

The testing of inclinometers and banking indicators depends on the construction, rather than on the use of the instrument. Temperature tests and observations concerning the quickness of action are essentially for liquid-filled instruments, regardless whether they are to be employed as inclinometers or banking indicators. Air-damped instruments are not likely to show excessive time lag, but should be examined for friction, looseness, and general accuracy, and the damping should be sufficient to prevent oscillation.

FIG. 13.—Sperry liquid damped fore-and-aft inclinometer.

Either type of instrument may be tested for time lag by pivoting the instrument with an initial upward inclination and then dropping it suddenly onto a slanting support at an equal angle below the horizon. The entire time of travel may be noted with a stop watch, and should not exceed about two seconds. It is important for this test to be repeated at temperatures fully as low as those which may be experienced in flight. Alcohol and other nonfreezing solutions have been used for filling the instruments. Inclinometers and banking indicators should also be tested under vibration. The bubble type of banking indicator has been found at times to show a systematic average displacement during vibration.

9. ABSOLUTE MEASUREMENT WITHOUT GYROSCOPES.

Both the dip needle and earth inductor have been frequently proposed for inclinometers.[5] Either the dip needle in conjunction with a magnetic compass, or the earth inductor without a compass, if arranged in multiple units, would serve as an inclinometer over any region of the earth's surface where the direction of the earth's field is known.

[5] The Earth Inductor as an Inclinometer, N. E. Dorsey, Journ. Terr. Mag. and Atmos. Elect. 18: 1-38, 1913; Induction Inclinometers, W. Uljanin, ibid., 24: 113-117, 1919.

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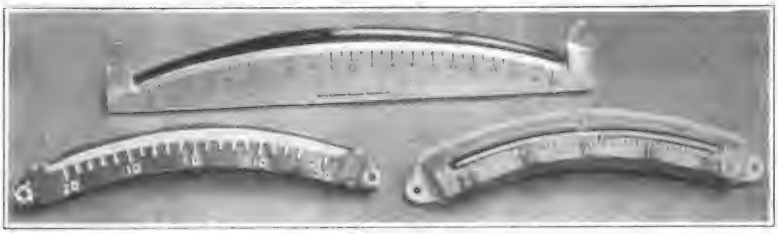

FIG. 14.—Bubble banking indicators.

FIG. 15.—Sperry pendulum banking indicator.

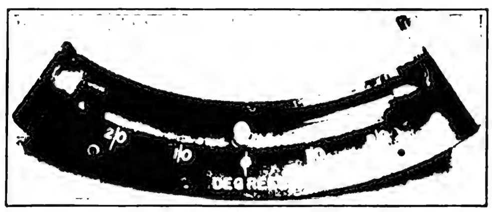

FIG. 16.—Luminous ball banking indicator.

FIG. 17.—Differential lateral inclinometer.

The inductor in its simplest form consists of a flat coil of copper wire connected to a suitable millivoltmeter; commutation is provided such as to build up a continuous electromotive force due to cutting the earth's field. The ordinary equations of the dynamo apply to this instrument and show that by sufficiently increasing the speed it can be made entirely practicable.

The recording sun camera developed by the British at Martlesham Heath gives an excellent tracing of the image of the sun, thus serving as a recording inclinometer when small corrections are made for the relative movement of the sun during the time of the flight.

Both in this country and elsewhere the reflection of an airplane in a smooth body of water below has been utilized for recording photographically the angular movement of the airplane.

The observation of the trajectory of a falling object, if made visible, will give information concerning the angular position of the aircraft, provided suitable allowance is made for the initial linear velocity of the falling body and for drift of trajectory due to wind. For the trajectory of such a body would be determined solely by its initial velocity, together with the true gravitational field of the earth, barring the effect of the wind. Thus the trajectory is uninfluenced by acceleration of the aircraft. In this way the difficulties characteristic of pendulum indicators can be avoided. It has been proposed [6] to apply this to an instrument inclosed in an air-tight case somewhat after the fashion of an hourglass. In this way the effect of the wind would be eliminated, but the trajectory would still be independent of aircraft accelerations. Instead of observing the falling particles of sand, a fine jet of mercury might be used.

There remain a number of possibilities for inclination measurement in a manner free from the usual errors of pendulum indicators, although not attaining completely the status of absolute measurement owing to the necessity for some assumption regarding the path of the airplane or the motion of the atmosphere. Under ordinary conditions these assumptions are entirely legitimate. A proposal of this kind by one of the present authors has been the use of a spring pendulum. The stretching of the spring serves to measure the excess of the apparent gravitational field, caused by centrifugal force over and above the true gravitational field. The angular deflection of the pendulum shows, as usual, the direction of apparent gravity. Thus the proper interpretation of this observation would go definitely one step beyond the simple, rigid pendulum toward giving the true inclination of the aircraft with respect to the ground. A second instrument developed by one of the authors likewise based on centrifugal force is shown in figure 17. This instrument is essentially a differential lateral inclinometer, and has elsewhere been referred to as the balance banking indicator. It consists of two equal masses practically balanced on a knife-edge. The center of gravity of the system is just slightly below the knife-edge. The instrument is mounted on the instrument board with the knife-edge parallel to the fore-and-aft axis of the aircraft, so that the beam of the balance may deflect in a plane parallel to the instrument board. The case of the instrument is filled with a damping liquid. Now, when the aircraft in its flight turns about a vertical axis, the two equal masses of the system, W^1 and W^2, share the same angular velocity but are located at different distances from that axis. Hence, the centrifugal force on one would be greater than that on the other, and the balance beam tends to remain perpendicular to the axis of rotation of the aircraft—that is, approximately horizontal. Thus, the angular deflection of the balance beam relative to a reference line on the case indicates the inclination of the aircraft relative to the ground while going around a bank.

The Aveline stabilizer, a recent French development,[7] automatically operates the controls of the ship by compressed air actuated by a combination inclinometer. The indicator element is in principle a mercury-filled inclinometer which, instead of operating on the usual liquid inclinometer principle, has an auxiliary correction for centrifugal force. This correction is automatically made by a device in the nature of a turn indicator, consisting of two Venturi tubes suitably connected and located at the respective extremities of the wings.

Until gyroscopic appliances can be reduced in bulk, weight, and expense, the development of these various semiabsolute methods of measurement seems to be a desirable field for further investigation.

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[6] The suggestion is believed to have originated with Mr. Benedict, a member of the Air Service, in 1918.

[7] Aerial Age Weekly, Vol. 12: pages 656–658, 667, 1921.

REPORT No. 128.

DIRECTION INSTRUMENTS.

PART II.

THE TESTING AND USE OF MAGNETIC COMPASSES FOR AIRPLANES.

By R. L. Sanford.

INTRODUCTION.

One of the most important and least satisfactory of all aeronautic instruments is the magnetic compass. Owing to the extraordinary conditions under which a compass must operate in flying, the ordinary marine type is impossible to use, and new and radically different designs have been found to be necessary. Unfortunately, even the best types of instrument which have so far been produced are unreliable under certain conditions. This fact has led most pilots to regard the compass with suspicion, and many have come to the conclusion that a compass should not be included in the instrumental equipment of an airplane. There are many times, however, when known landmarks are not available, and it is necessary to rely upon the indications of the compass. It is essential, therefore, that the pilot should understand the characteristics of his compass in order that he may know under what conditions its indications are reliable. An understanding of the principles involved may also enable pilots to offer valuable suggestions as to design and use as the results of experience and observation.

TESTING.

Before installing a compass in an airplane it should be carefully inspected and tested to be sure that there are no defects of material or workmanship and that it is in good working order. These points can easily be determined by means of simple laboratory tests. The performance characteristics which are inherent in all instruments as distinguished from their behavior under actual flying conditions are pivot friction, calibration, period, and damping. In some cases it is desirable to measure the strength or magnetic moment of the needles but usually this is not necessary as weak needles are indicated by too long a period.

PIVOT FRICTION.

Excessive pivot friction in a compass reduces its sensitivity to small changes of direction and is generally evidence of damage or imperfection in material or workmanship. This point therefore is generally the first to be considered in the testing of a magnetic compass. The only auxiliary apparatus required for this test is a small magnet or, better, a coil by means of which the compass may be given a momentary deflection. In practice the compass under test is deflected by various small angles in each direction and the amount by which it fails to return to its original resting point noted. This procedure is repeated with the compass oriented in different directions, usually on headings corresponding to each of the cardinal points. The pivot friction as determined in this manner is rarely a constant quantity but there is generally no difficulty in deciding whether or not an instrument has an excessive amount. When released from an initial deflection of 5° in either direction a good compass should return to its original position to within 1°.

CALIBRATION.

The term calibration expresses the accuracy with which a compass indicates direction on any heading exclusive of the effect of pivot friction which can generally be removed by tapping. There are several factors which determine the accuracy of calibration of a compass, namely: (1) The orientation of the magnetic needles on the card; (2) the accuracy of the graduation on the card or scale; (3) accuracy of centering of the pivot; (4) magnetic materials in the bowl or mounting; (5) location of the lubber line.

The magnetic needles should be mounted parallel to the north-south line on the card. If this is not done there will be a constant error on all headings equal to the angle of error in mounting.

In good instruments the errors in graduation of the card are usually neglibible. Graduation errors may be in either direction and varying in amount.

If the pivot is not correctly centered on the card the resulting eccentricity error varies from zero to a maximum value depending on the heading and the amount by which the pivot is off center.

The presence of magnetic materials in the bowl or mounting may produce errors in reading depending upon the amount and location of such impurities.

While it is generally possible to separate these errors it is usually not necessary to do so except for the purpose of discovering the cause of an excessive error.

For determining the calibration errors of compasses a simple testing stand has been constructed. This stand is shown in figure 1. It consists of a rotating table graduated around its edge so that by means of a vernier index angles of rotation can be read to 0.1°. Two telescopes are carried on an adjustable support which are used for sighting on horizontal card compasses. If compasses having vertical cards are to be tested an auxiliary stand is used. This stand has upon its base a horizontal line which is at right angles to the plane of the back of the stand. It also has provision for tilting with a scale for measuring the angle of tilt. An airplane compass card should be free to turn when the compass is tilted 20° in any direction.

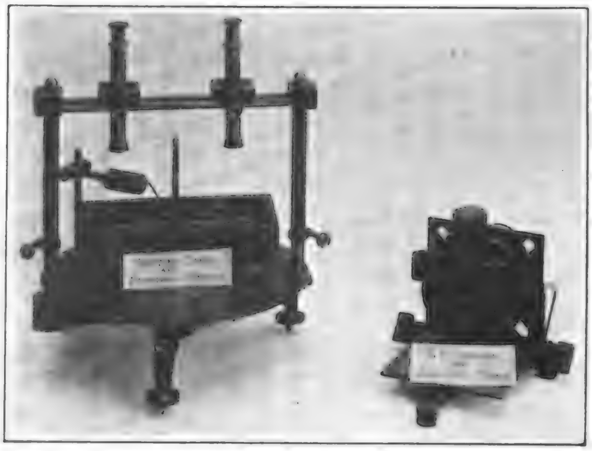

FIG. 1.—Compass testing stand.

The standard compass, also shown in the figure, consists of a single magnetic needle having a sapphire cup and suspended on a diamond pivot. The pivot friction of this combination has been found to be entirely negligible. Upon the upper side of this needle is a line which is accurately parallel to its magnetic axis. The needle is pointed and the points lie in the vertical plane passing through the index line. It is therefore possible to check the parallelism of the index line and the magnetic axis by taking observations with the needle in its normal position and inverted.

When a compass is to be tested, it is set on the stand and the telescopes focused on the north and south points of the card, or if it has a vertical card the auxiliary stand is used and the telescopes are focused on its index line. The compass is then placed at a distance and the standard compass substituted and raised or lowered on an adjustable base until the index line is in focus. The telescopes are not disturbed after the initial adjustment. When the stand is so oriented that the index line of the standard compass is focused on the cross hairs the vernier index is set to zero. The standard compass is then taken away and the other compass replaced. If the table is rotated till the north-south line is on the cross hairs of the two telescopes, the angle read on the vernier shows the error on the north heading. The error on any other heading can be determined by rotating the table through any desired angle and

noting the difference between the compass reading and the table reading. After the test has been completed a check reading on the standard compass is taken in order to be sure that the direction of the magnetic meridian has not changed while the observations are in progress. The ordinary type of airplane compass graduated with 10° division should not be in error on any heading by more than 2°.

PERIOD.

For any particular type of compass, since the moment of inertia of the moving system is practically the same for all instruments, the period, measured at the same place or at different places where the horizontal intensity of the earth's magnetic field is the same value, is a good indication of the strength of the magnetic needles. An excessively long period is an indication of weak needles. For compasses having considerable damping it is difficult to determine the complete period (the time interval between successive transits in the same direction through the position of equilibrium) and it is necessary to determine the half period. This is accomplished by setting the card to swinging by means of a coil or small magnet and noting, by the aid of a stop watch, the time interval between successive transits through the equilibrium position. The variations in the horizontal intensity of the earth's magnetic field are such that the period of the same compass will not be the same in different parts of the earth. For instance, a compass having a period of 20 seconds in Washington would have a period of 23 seconds in Bangor, Me., and 17 seconds in New Orleans. Various types of airplane compasses are designed to have widely different periods (from approximately 10 to 50 seconds) and opinion differs as to the most desirable value. One type of instrument developed during the war has a complete period of approximately 15 seconds.

DAMPING.

The liquid which is used in the majority of airplane compasses, besides taking some of the weight from the pivot, is for the purpose of damping out oscillations of the card and so enable the compass to give a steady reading. For the purpose of comparing the degree of damping of various airplane compasses the "damping constant" has been defined as the ratio of consecutive deflections on the same side of equilibrium when the card is swinging. In order to obtain truly comparable values, it is necessary to make the determination from the same value of initial swing which is usually taken as 45°. It is not proper to take the observations for damping by releasing the card from the required initial deflection. The system must be swinging freely. The degree of damping varies quite widely in instruments of different design. The specifications for one type used during the war stipulated that the damping constant should be not less than 15 nor more than 45.

INSTALLATION AND ADJUSTMENT.

The location of a compass in an airplane is of considerable importance. The instrument must be so placed that the pilot can read it at a glance without changing his position. In order to avoid parallax errors, the line of sight when reading should be in the plane through the lubber line and the pivot. Another consideration in the location of the compass is the presence in the plane of magnetic material which will cause deviations of the compass needles and consequent errors in reading. The effect of stationary metal parts can generally be neutralized by the use of small compensating magnets placed in tubes provided for the purpose. The effect of moving iron parts can not be neutralized, however. The ignition system is also a source of trouble in some planes and may cause errors amounting to as much as 10 or 15 degrees. This difficulty is so great in some cases that the possibility of placing the compass at a distance (on the tail or wings, for instance) has been seriously considered. This condition points to the necessity of carefully considering the requirements of the compass when designing an airplane.

SOURCES OF UNRELIABILITY.

Assuming that the results of laboratory tests are satisfactory and that the effect of magnetic material in the airplane has been completely neutralized by means of the adjusting magnets there are still sources of error under certain conditions in flight. The most important of these sources of unreliability are vibration and rapid accelerations and quick turns.

Because of the fact that the center of gravity of the compass card is below the point of support it acts as a pendulum. The result is that vibrations of the point of support of sufficient amplitude and certain frequencies will cause deflections or in extreme cases actual rotation or "spinning" of the card. If there is excessive pivot friction or the pivot and cup do not have the proper corresponding shapes there may also be deviations or turning due to a sort of "ratchet effect" between the pivot and cup. These are largely overcome in most instruments by proper antivibration mountings which absorb the vibrations. The ordinary gimbal mounting should never be used. It is on account of vibration effects that the pivot is on the card instead of the cup as is customary in marine instruments.

There are two possible effects due to rapid turns and straight accelerations. On quick turns the liquid in the compass may be set into rotation and drag the card with it. This is largely overcome by making the clearance between the card and the bowl large. This reduces the effect, as the liquid in contact with the sides of the bowl is most affected. Another way of preventing the liquid from being set into rotation to an appreciable extent is to make the bowl of approximately spherical shape.

The other effect of turns and acceleration is of a different nature. It is a well-known fact that the direction of the earth's magnetic field is not horizontal. The angle of inclination or "dip" varies in different parts of the world from zero at the "magnetic equator" to 90° at the magnetic pole. In a compass the vertical component is balanced by a small mass on one side of the point of support. For this reason the horizontal component is the only one that exerts a directive force on the card. When an airplane makes a quick turn the resultant effect of gravity and centrifugal force is such that the plane of the card is inclined to the horizontal. The vertical component of the earth's magnetic field then has a component in the plane of the card and this exerts a directive force. The direction in which the card will tend to turn will be the direction of the resultant of the horizontal component of the earth's field and the component of the vertical force which is in the direction of the plane of the card. This causes an error which depends upon the angle of bank and the duration of the turn. This effect is most noticeable when turning east or west from a northerly course and hence is usually termed the "northerly turning error." In this case the north end of the card is drawn down and if it turns rapidly enough may even indicate that a turn has been made in the opposite direction from that actually made. It is readily apparent that under such condition a pilot who is flying in clouds and whose airplane is turned by gusts may think he has turned in the opposite direction from what is actually the case and in attempting to correct his direction will turn still more and may eventually find himself in a spin. Pilots are generally warned against taking a northerly course in flying through clouds.

The actual direction of the card at any instant depends not only on the angle of inclination but also on its period. A compass with a very long period for instance may take so long to respond to the disturbing force that the turn may be completed before there is an appreciable error in its reading. A very long period compass has been strongly recommended by some and undoubtedly is much less affected by the "northerly turning error" than one with a short period but in practice it is so sluggish that it is unsatisfactory for use under ordinary conditions. It is generally considered preferable to use a short period instrument which can be read more quickly after any disturbance and not to rely on its indications when the conditions are known to exist which render it unreliable. A good short period compass in connection with a reliable turn indicator seems to be the best combination so far suggested.

REPORT No. 128.

DIRECTION INSTRUMENTS.

PART III.

AIRCRAFT COMPASSES—DESCRIPTION AND CLASSIFICATION.

By John A. C. Warner.

SUMMARY.

This part contains a brief general treatment of the important features of construction of aircraft compasses, and descriptions of the principal types used in America and in foreign countries. Brief mention is also made of several compasses now in process of development but not in production. At the conclusion of this part will be found a descriptive tabular classification of the various instruments included in the text.

INTRODUCTORY.

There is probably no aircraft instrument which has been the subject of more careful and serious study than has the magnetic compass. Its supreme importance to the navigator of the air accounts for the energy which has been devoted toward its perfection. But with all the attention it has received there still remains the possibility of vast improvement. The working conditions are different and much more severe for the aircraft compass than for its marine prototype and it has been necessary to make important modifications in the latter in order to adapt it to use in aviation. It is the purpose of this paper to discuss the more important characteristic features of construction of the aircraft compass and to describe the principal American and foreign types which have been put into production. In Report No. 131, Section VII of this series, under the title "Aerial Navigation and Navigating Instruments," will be found a discussion of the use of the compass and its errors. Part III of this report, entitled "The Testing and Use of Magnetic Compasses for Airplanes," contains additional material not elsewhere considered.

GENERAL FEATURES OF CONSTRUCTION.

The common types of magnetic compass used on aircraft comprise the following principal parts with elements as noted:

1. Rotating system—
   - *a.* Card.
   - *b.* Float chamber (in liquid damped type).
   - *c.* Magnetic elements.
   - *d.* Bearing member.
2. Bowl—
   - *a.* Container.
   - *b.* Damping medium.
   - *c.* Expansion chamber.
   - *d.* Lower bearing member.
   - *e.* Lubber-line and divided scale.
   - *f.* Observation openings.
   - *g.* Illuminating device.
3. Compensating device.
4. Mounting support.

ROTATING SYSTEM.

Card.—Two principal card forms are noted, the horizontal and the vertical. Not a few instruments combine the two forms and make possible either horizontal or vertical observations. Furthermore, horizontal card instruments are often provided with a prism which allows observations to be made in either a horizontal or vertical direction. When the latter device is employed it is necessary that the card have two scales, one for the direct reading and a second scale with characters inverted and reversed for prism observations. The different systems of marking are described in a following section of this paper. It is important that the characters and divisions of the card be clear and large so as not to require too great an effort on the part of the pilot in making readings. Provision is often made for the use of the compass at night by marking the principal divisions and characters with self-luminous material. This feature is of use only at times of extreme darkness in the immediate vicinity of the compass since the material is ordinarily not sufficiently brilliant to render the markings visible under conditions of dim lighting from another source.

Float.—The card is commonly carried by a hollow water-tight float chamber filled with air and properly supported and guided in a surrounding body of liquid held in the bowl container. In order to minimize the effect of liquid drag, the float chamber is invariably made in the form of a hollow body of revolution (usually a somewhat modified cylinder or ellipsoid) symmetrical about an axis perpendicular to the card. Liquid drag is caused by the tendency of the liquid, when it takes up a swirling or rotative motion with changes of heading of the aircraft, to drag the float with it. The float serves to relieve the pivot bearing, upon which it is supported, of most of the weight of the rotating system. This is important since the magnitude of the vibrational difficulties and frictional error to which the card is subject are largely dependent upon the weight on the bearing. By reducing this weight to a minimum it is also possible to prolong the life of the pivot support which tends to become misshapen under excessive vibration and shock. Several instruments, notably the Creagh-Osborne Type 5/17, have rotating systems so light as to require no float. This, of course, is also true of the dry type of compass in which no liquid is used.

Magnetic elements.—The magnetic elements upon which the compass depends for its action are usually formed of small cylindrical or flat magnetized needles or rods (2 to 12 in number) of hardened alloy steel attached either within the float chamber or upon its lower surface. In certain types they are suspended upon wires below the card. Numerous dispositions of these elements will be noted in referring to the descriptions which follow. The choice and position of these elements is an important factor governing the action of the rotating system. With compasses in which the elements are surrounded by a damping liquid having a corrosive effect upon steel, the magnets are either plated or covered by a noncorroding metal.

The moment of inertia of the rotating system depends to some extent upon the size, number, and position of these elements; the magnetic moment and, in turn, the period of the compass are also dependent upon these factors. It is necessary, then, in practice to so select and mount the magnets that the operating requirements will be satisfied as completely as possible.

Bearing member.—In most of the older types of aircraft compass the rotating system was supported upon a bearing composed of a cup or socket fixed centrally upon the rotating part and resting upon a pivot attached to the bowl. The more recent practice reverses this arrangement and we find practically all of the modern instruments with the pivot on the movable element and the cup mounted below upon a bearing post attached to the bowl. This results in an improvement in the stability of the card.

Brief consideration of the problem will show that the pivot forms a most important element of the compass and must be carefully designed. It is often subjected to violent shocks which it should withstand without breaking or becoming blunted. Otherwise, the action of the compass will become very unsatisfactory. Various materials are used for pivots, including iridium and alloys of iridium, special alloy steels, and agate. One of the most common combinations is agate for the pivot and sapphire for the cup. It is usual practice to select a pivot of

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material slightly softer than the cup upon which it bears, otherwise the surface of the cup would be roughened owing to the cutting action of the pivot. The radius of curvature of the pivot point is made smaller than that of the cup.

BOWL.

Container.—The compass bowl acts as a container for the damping medium. It is usually made cylindrical in form in order to reduce as much as possible the swirling or rotation of the inclosed damping fluid when changes of heading take place. One of the instruments later described was designed to overcome this effect to a very large degree by the use of a completely spherical bowl. The usual well designed bowls do not, however, go to this extreme. A generous clearance should be allowed between the card and the wall of the bowl so that the swirling error will be relatively small.

Damping medium.—It is the function of the damping medium inclosed within the bowl and surrounding the rotating system, first (in the case of liquid damping), to reduce the weight of the moving system on the pivot bearing, thus protecting the bearing from shock, and reducing errors due to friction and vibration as described above; second, to damp excessive oscillations of the rotating system and thus improve the stability and action of the card. The amount of damping depends upon the viscosity of the damping medium as well as upon the construction of the movable parts. In air-damped compasses the action of the moving parts against the inclosed air produces the damping effect. In this case it is obviously necessary for the rotating system to present a greater surface to the action of the air than is the case with liquid-damped instruments. The Favé compass, shown in Fig. 18, is an example of this type.

It is important that the damping medium shall be such as to maintain a practically constant viscosity within the range of temperatures experienced in service. Pure alcohol is sometimes used, but it has the disadvantage of more or less rapidly dissolving practically any existing type of paint with which it comes in contact. This action destroys the permanency of the card markings and results in a formation of a deposit of sediment upon the bearing, thus introducing a friction error. Alcohol diluted with some other liquid is most often used, a common mixture being 30 per cent alcohol to 70 per cent distilled water. Colorless, acid-free kerosene is also employed in certain compasses. The liquid is introduced into the bowl through a tapped and plugged filler hole in the wall.

Expansion chamber.—The volumetric changes in the body of liquid confined within the closed bowl are cared for in two different ways. The device most frequently employed is an expansion chamber composed of one or more thin metal diaphragm boxes, similar to those used in aneroids, communicating with the interior of the bowl. In certain compasses the expansion is compensated by the use of a single corrugated diaphragm forming the base of the bowl. A second method for overcoming this difficulty is to mount a small hollow chamber at the top of the bowl so that the excess liquid may flow into it from the bowl when expansion takes place. This device also serves as an air trap to which bubbles from the liquid may rise, thus avoiding any objectionable action resulting from their presence in the liquid.

Lower bearing member.—A polished sapphire or garnet cup held in a brass socket is most often employed as the lower bearing member in which the pivot of the rotating element rests. In many instances the jewel is set in a socket which is free to move a short distance vertically against a shock-absorbing spring. A second method for relieving the shock effects to some extent is to set the jewel against a layer of rubber or cork which acts as a cushion. The bearing post which supports the cup is fixed to a bridge member attached to the base of the bowl.

Lubber-line and divided scale.—In order that accurate observations may be made of the position of the compass card relative to the bowl, a reference marking or lubber-line is usually placed inside the bowl at the side where the observations are to be made. The instrument should be mounted so that a line passing through this lubber-line and the pivot of the compass is parallel to the longitudinal axis of the aircraft. A divided scale (starting from a point above the lubber-line) is often found at the upper rim of the bowl above the observation glass. A sliding index or pointer is used in conjunction with this scale in course setting and taking bearings.

Observation openings.—Observations of the horizontal card are made through a cover-glass held by a bezel ring which joins it to the upper rim of the bowl. The joint is made tight by the use of a rubber gasket. Vertical card observations are made either through a small glass-covered opening in the side of the bowl or, in certain compasses, through the cylindrical glass bowl container itself. The latter arrangement has the advantage of magnifying the divisions and characters of the card, due to lens effect caused by the convexity of the glass.

Illuminating device.—Modern compasses are provided with a miniature electric lamp so mounted in a shielding socket as to illuminate the card. In some instances a special opening (covered by ground glass to prevent glare) is provided either in the base or side wall of the bowl so that the light rays may enter. Designs which do not allow the light to fall directly upon the card should provide for illumination either by transparency of the card or by reflection from properly painted interior walls of the bowl.

COMPENSATING DEVICE.

Owing to the presence of magnetic fields set up by the power plant and auxiliaries of the aircraft system it is necessary to provide a compensating device to minimize the disturbing influences of these fields. Small bar magnets suitably placed relative to the magnetic elements of the card are employed to neutralize the effect of objectionable extraneous fields. A common form of compensating device is that consisting of a vertical slotted or grooved rod mounted directly below the bowl and carrying two sliding collars, adjustable in a vertical direction only, thus making it possible to vary the distance between the card and the correcting bar magnets (usually two in number) which are carried by each collar. The correcting magnets attached to one of the collars are secured with their longitudinal axes parallel to the fore-and-aft line of the aircraft while the axes of the second set extend parallel to the athwartships line. The compensation is governed by the number, strength, and position of these members.

Another form of compensating device consists of a holder mounted upon the bowl directly above or below the card (and sometimes in both positions), centered relative to its axis. The holder contains a fore-and-aft and an athwartships tube in which the small correcting magnets are placed. In this case the amount of compensation is governed by the number and strength of the magnets employed.

A third device for compensation consists of an arrangement of four tubular holders so mounted on the sides of the bowl or bowl housing that the correcting elements may be properly placed in fore-and-aft and athwartships positions. This disposition as well as the preceding one have the advantage of compactness and ease of manipulation.

MOUNTING SUPPORT.

In view of the excessive vibrations existing on aircraft and their ill effect upon the compass it is advisable to provide the instrument with a mounting which will reduce the influence of vibration as much as possible. This is usually accomplished in one of three ways: first, by inclosing the bowl in a housing lined with antivibrational material, such as felt or horse hair, to overcome the vertical shocks and with flat metal springs properly placed to relieve vibration and shock in a horizontal plane; second, by mounting the bowl upon supports or cushions of felt or fibrous material and with spiral metal springs to oppose horizontal effects; third, by attaching the bowl mounting to the aircraft with rubber cushions at the points of attachment. Certain deviations from these usual arrangements will be noted by referring to the descriptions and photographs of the individual instruments. Certain of the older types and many of the present foreign compasses are swung in gimbals. This practice is not to be recommended for airplane installations but is not without merit for airship service where excessive vibration and violent accelerations are not as prevalent.

In the pages which follow will be found illustrations and descriptions of the principal types of aircraft compasses which have been used in America and abroad. Some of the most important details of the instruments described have been classified in tabular form at the conclusion of the paper.

DESCRIPTIONS OF AMERICAN COMPASSES.

GENERAL ELECTRIC AIR COMPASS TYPE B.

The liquid damped compass (acid-free kerosene damping-fluid) shown at the left of figure 1 is widely used in the military aircraft of this country. Many of its features are patterned after those of the original British Creagh-Osborne 5/17 compass, and its appearance closely resembles that of the British instrument.

The card has the form of a truncated cone with smaller diameter of 43 millimeters at the top and flaring to a diameter of approximately 54 millimeters at the bottom. (See illustration of rotating element and bearing post at right of Fig. 1.) The markings are found upon the exterior face of the cone, which has a depth of 10 millimeters along a generating element. The card is lettered at the cardinal points with luminous material and divided each 10°, with numerals marking each third division, at which luminous dots are also painted. Four light spokes, extending from the pivot mounting at the center, serve to support the card ring.

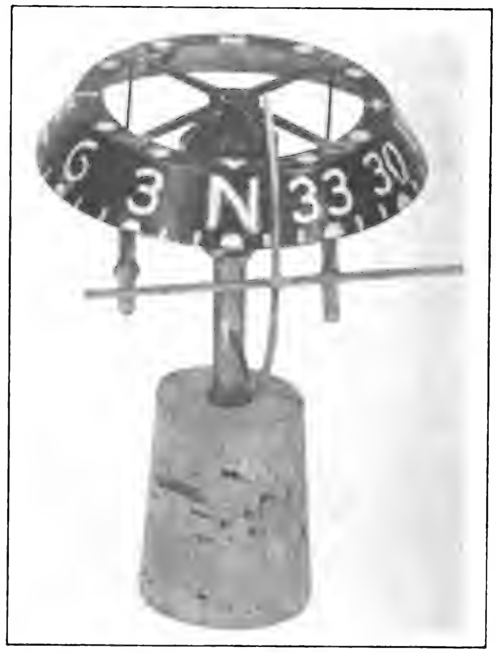

FIG. 1.—General Electric air compass, Type B.

The pivot is of special alloy and rests in a sapphire cup mounted upon a bearing post attached to the lower surface of the bowl. The pivot is prevented from leaving its socket by a split cage, the two halves of which are screwed to the bearing post, and their upper edges bent inward so as to overhang a bell-shaped hood member just above the pivot on the rotating element. The two bar magnets of tungsten steel (50 millimeters long and 29 millimeters between centers) are suspended upon four wires extending from the card ring.

A vertical wire painted with luminous material is attached near the lower extremity of the bearing post and extends upward toward the front of the bowl to serve as a lubber-line. A horizontal wire is attached to the lubber-line wire and forms a reference relative to the lower line of the card thus making it possible to use the compass as an inclinometer.

The main body of the bowl is spherical in shape and has an interior diameter of approximately 85 millimeters. The bowl projects toward the front in a cylindrical extension (with axis inclined at approximately 26° above the horizontal) which is capped by the glass observation window (68 millimeters diameter) held in place by a bezel ring and inclined backward at an angle of approximately 26° from the vertical. A miniature incandescent lamp in shielding socket is attached to the bezel ring at the top and provides illumination for the card at times when the luminous markings are not clearly visible.

Mounted at the top of the bowl and communicating with the interior is a combination air trap and expansion chamber. A filler plug is provided in this cylindrical chamber as well as in the back wall of the bowl itself. Liquid expansion is cared for by this device and any bubbles which may form in the damping fluid rise to the surface in the chamber and produce no objectionable effects. The compensation chamber surmounts this air trap and consists of two brass tubes (one along the fore-and-aft line and the other athwartships) of diameter great enough to accommodate several correcting bar magnets. The compensating device is covered by a brass cap which prevents the magnets from slipping out.

Three lugs as shown in the illustration project from the bowl and rest upon antivibrational supports projecting from the main mounting bracket. Each of the three lugs rests upon a felt washer acting as a cushion for vertical shocks, while a flat spiral spring fastened to a bolt from the lug and centered in a cylindrical cup at the under side of each bracket lug serves to relieve vibration effects in a horizontal plane.

The compass above described has a period of 12 seconds and a damping constant of 20. The card is free to swing when the compass bowl is tilted 30° from its normal position. The instrument weighs 2.5 pounds.

AMERICAN MODIFICATIONS OF THE CREAGH-OSBORNE AIR COMPASS, TYPE 5/17.

The production during the war of the type B compass previously described exceeded that of the other modifications of the Creagh-Osborne air compass, type 5/17. However, several other instruments of this same general type were produced in limited quantities.

FIG. 2.—Air compass, Type A.

FIG. 3.—Navy standard compass No. 1.

A compass known as the Creagh-Osborne air compass Mark VIII, so nearly duplicates the British instrument later described that no space will be devoted to its treatment at this point.

The instrument shown by figure 2 is known as the type A. The mounting is different from that of the British instrument and it is somewhat smaller in size. The illustration shows the instrument without the incandescent lamp illuminating device in place.

Several other modified instruments of less importance than those already mentioned were manufactured in very limited numbers.

NAVY STANDARD COMPASS NO. I.

The Sperry aircraft compass Mark XVI, also known as the Navy standard compass No. I (fig. 3), is a type widely used in aircraft. The large flying boats and military bombing airplanes ordinarily carry an instrument of this general type as standard equipment, while a somewhat smaller model, known as the Navy standard compass No. II, is used on the smaller

airplanes. The instrument to be described has a 76-millimeter card while the smaller model has a card 50 millimeters in diameter.

The card of the Navy standard compass No. I is of the combination horizontal and vertical type with divisions each 5°. Numerals mark the 30° points and the cardinal points are lettered. The top or horizontal surface has a diameter of approximately 76 millimeters, while the vertical card surface, cylindrical in form, has a diameter of 63 millimeters and a depth of 19 millimeters. These cards are carried by a float chamber with the magnetic elements inclosed within.

The alloy pivot mounted in a recessed cavity in the lower surface of the float rests upon a sapphire cup mounted upon a bearing post in a shock-absorbing spring socket. The post is attached centrally upon a bridge member at the center of the bowl base. A vertical curved lubber-line wire is provided both at the front and rear of the bowl, one for vertical and the other for horizontal reading. The markings upon the horizontal card surface start 180° from those of the vertical card so that the readings of the former are taken with reference to the back lubber-line while those of the latter are made with the forward line as reference.

A cylindrical ring of glass (109 millimeters inside diameter and 56 millimeters in height) forms the vertical walls of the bowl and rests upon the base casting where a rubber gasket is used to make a tight joint. Viewing the vertical card through the cylindrical bowl causes magnification of the card due to lens effect. The bowl ring is surmounted by an aluminum ring with four lugs extending from the sides; the top surface of this ring bears 5° divisions with numerals at each 10° point. Within this outer member is mounted a rotatable ring carrying sights which are intended for use in taking bearings and in making drift observations. The cover-glass is clamped against a rubber gasket resting upon the top surface of the cylindrical bowl glass by means of four bolts passing through the four lugs and corresponding projections of the aluminum base casting.

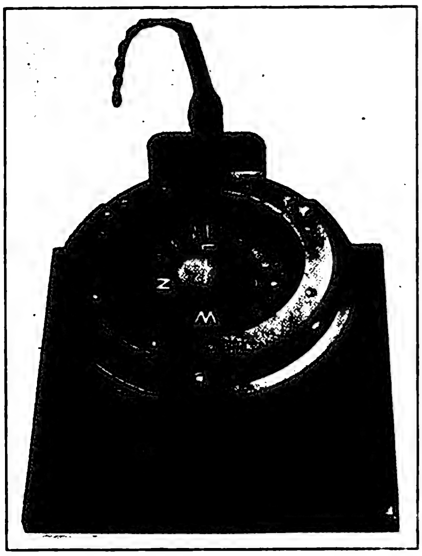

FIG. 4.—Creagh-Osborne air compass (Sperry) Mark II.

A hole through the base communicates with a single diaphragm expansion box contained within a protective housing. This housing also serves the purpose of an auxiliary base plate and carries the compensation box at the center. The latter is of the ordinary type with a fore-and-aft and an athwartships tube acting as holders for the correcting magnets. A filler hole passes through the base casting. The instrument is so designed that it can be mounted upon either a horizontal or vertical surface by using the proper mounting plates.

The period of the compass is approximately 20 seconds and the damping constant 5. The weight is approximately 3.7 pounds.

CREAGH-OSBORNE AIR COMPASS (SPERRY) MARK II.

The compass known as the Creagh-Osborne air compass (Sperry) Mark II (fig. 4) is of the liquid damped type (alcohol mixture) with a horizontal card.

The mica card (76 millimeters diameter), divided each 5° and with luminous markings and numerals at each 10° point, is carried by a float chamber of usual form. The alloy pivot is mounted in a recessed cavity in the lower surface of the float and rests upon a sapphire cup held in a cup socket. This socket in turn rests upon a shock-absorbing spring in the hollow section of the bearing post. The latter is held by a short bridge member at the center of the base of the bowl.

The bowl has an inside diameter of approximately 108 millimeters and a depth of 42 millimeters. A luminous wire lubber-line is found at the back of the bowl at the point where a window is mounted in the wall to allow for illumination from an incandescent lamp attached outside. A diaphragm expansion chamber is centrally fixed to the underside of the bowl.

The bowl rests upon three antivibrational rubber-covered rods extending from the walls and held by corresponding suspension cradles attached to the inner surface of a protective housing which surrounds the bowl. This housing is lined with horsehair so as to provide a cushion for the bowl. A filler hole extends through the side wall of the latter. The instrument is designed to be mounted upon a horizontal surface by means of four bolts in the base of the housing with rubber shock-absorbing collars attached.

Compensation of the type shown in the illustration is effected by means of a compensation block made of wood, with holes to hold the necessary correcting magnets. This block is fastened either above or below the card with its vertical axis extended coinciding with that of the bearing post. Another model of this instrument has four compensation tubes attached to the outer wall of the housing, one pair being parallel to the fore-and-aft line of the aircraft and the other athwartships. The required number of magnets are placed within these tubes.

The Mark II instrument has a period of approximately 18 seconds and a damping constant of 10. It weighs approximately 3.3 pounds.

PENTZ COMPASS.

The design of the Pentz liquid (kerosene) damped compass (fig. 5) is a departure from the usual practice. The entire compass system, including card, bearing, and bearing post, is held suspended by a float chamber in the damping liquid within the spherical bowl.

FIG. 5.—Pentz compass.

Extending downward from the float (60 millimeters diameter) and attached at points diametrically opposite each other are two light flat rods, at the lower extremities of which is attached a horizontal wire ring approximately 92 millimeters in diameter. The bearing post, centrally located and supporting a sapphire cup at its upper extremity, is suspended from two wires, extending downward from the ring to the lower end of the post. This arrangement will be understood by referring to the illustration at the left of figure 5.

The card and magnetic element are very nearly identical with those employed in the General Electric type B compass previously described, the principal dimensions being the same. The point of difference lies in the manner of preventing the alloy pivot from leaving the cup socket. The ball and socket cage of the type B instrument is replaced in the Pentz by a shallow pan-shaped member attached to the upper surface of the card frame and restricted in vertical motion by coming in contact with the lower surface of the float before the card has lifted far enough for the pivot to leave the socket in which the jewel cup is held.

The designer of this instrument has endeavored to overcome the errors due to swirling, by inclosing the system described above in a spherical bowl the upper half of which (95 millimeters inside diameter) is of glass and the lower half of brass. The apparent size of the card when viewed through the sphere is magnified. A tight joint between the hemispherical halves is secured by means of a rubber gasket and a screw collar threaded to a shoulder forming part of the lower half. This shoulder overhangs the ring-shaped base of the mounting bracket and three felt, spiral spring, antivibrational supports similar to those used in the Creagh-Osborne compass support the bowl. A combination air trap, expansion chamber, and compensation box similar to the Creagh-Osborne device surmounts the bowl. A wire lubber-line is mounted both inside and outside the bowl, and parallax is avoided by sighting past the two lines.

This instrument, in addition to its capacity as a compass, is useful as an inclinometer. When used in this service a circular spot painted centrally upon the top float surface is observed with reference to a small circle cut upon the glass with the top pole of the sphere as center. A second circle engraved upon the glass at the equator is used with reference to the 92-millimeter wire ring which forms part of the floating system within the bowl.

The Pentz compass has a period of about 12 seconds and a damping constant of 40. It weighs about 3.3 pounds.

DESCRIPTIONS OF BRITISH COMPASSES.

CREAGH-OSBORNE AIR COMPASS, TYPE 5/17.

The Creagh-Osborne air compass, type 5/17 (fig. 6) has been one of the most widely used aircraft compasses. It is best adapted to service on scout planes where the advantages of a quick period instrument are desired. The compass is of the liquid damped type (alcohol of 0.84 specific gravity damping fluid) and is equipped with a card totally different from that employed in most compasses.

The card consists of a pan-shaped thin section of white metal (48 millimeters greatest diameter), which with the magnetic elements and pivot is so light as to require no float. The horizontal base surface of the card is cut away so as to leave four spoke members extending outward from the center to support the rim; the lower edge of the latter is inclined inward toward the pivot at an angle of 30° from the vertical. The two bar magnets (40 millimeters length) are suspended below the card (25 millimeters between centers) upon wire suspensions. The agate pivot is mounted upon a brass stem attached at the center of the card and rests in a sapphire cup held on a central post. A vertical adjustable wire extends from the inside

FIG. 6.—Creagh-Osborne air compass, Type 5/17.

FIG. 7.—Creagh-Osborne aero compass, Type 259.

upper surface of the bowl to within a short distance from the top center of the card and prevents the latter from leaving the cup bearing. The lubber-line fixture is mounted inside the bowl, as shown by the illustration.

The bowl is approximately spherical (80 millimeters inside diameter) except at the front where a short cylindrical projection extends inclined at an angle of 26° above the horizontal. This extension is capped by the cover-glass inclined back from the lower edge at an angle of 26° from the vertical. A nonleak joint is made between cover-glass and bezel ring by the use of a rubber gasket. An air trap and also a chamber for holding the compensating magnets in proper position are mounted at the top of the bowl. The air trap is arranged so as to collect any air bubbles which may form in the liquid and to allow for liquid expansion. Two filler holes are provided, one upon the air trap and the other upon the bowl itself.

The bowl is fitted with three lugs which hold it upon the supporting members of the mounting bracket. Felt washers at the points of attachment between the bracket lugs care for vertical vibration, while flat spiral springs are provided at the points of support to relieve the horizontal vibrations. A small electric bulb mounted with suitable shield upon the verge ring provides illumination for the card.

The Creagh-Osborne air compass has a period of from 8 to 10 seconds and weighs 2.8 pounds.

CREAGH-OSBORNE AERO COMPASS, TYPE 259.

The Creagh-Osborne aero compass, type 259 (fig. 7) is of the vertical card, liquid-damped type (alcohol mixture damping liquid). The card is formed of a mica band (50 millimeters in diameter and 13 millimeters in height) divided at 10° intervals and with luminous numerals every 30°. The cardinal points are lettered with luminous material. The card is carried by a float chamber with recessed cavity in its lower surface where the agate pivot is mounted upon a brass stem. The pivot rests upon a sapphire cup held in a socket at the upper extremity of the bearing post, the latter being mounted upon the bowl base. The float is restricted in vertical motion by a wire extending from the top of the bowl with a small hood at its lower extremity. This hood comes directly over the center of the float and prevents it from lifting far enough for the pivot to slip from the cup socket.

The main bowl chamber is approximately spherical (70 millimeters inside diameter) with a forward extension of circular section to which the vertical glass is attached, and with diaphragm expansion chamber at the back in a protective housing. A luminous lubber-line and a horizontal reference line are mounted inside the bowl, as shown in the illustration. The clearance between card and lubber-line is 12 millimeters.


FIG. 8.—Creagh-Osborne aero compass, Type 253.

Four lugs attached to the bowl provide for mounting upon the surrounding bracket ring with corresponding mounting clips. Felt washers and light compression springs are used at the points of attachment to take up vibration. A cylindrical box to contain compensating magnets is attached at the top of the ring, while a pedestal properly drilled for mounting is bolted at the lower side.

The compass described above has a period of approximately 25 seconds and weighs 2.1 pounds.

A much larger model of this instrument has been constructed and is known as type 256.

CREAGH-OSBORNE AERO COMPASS, TYPE 253.

The Creagh-Osborne aero compass, type 253 (fig. 8), is designed for use on the larger types of aircraft. This compass is liquid damped (alcohol damping fluid) and is provided with a mica horizontal card 112 millimeters in diameter mounted upon a suitable float chamber. An agate pivot in a recessed cavity in the lower float surface rests upon a sapphire cup on the bearing post.

The bowl is of brass, has an inside diameter of 150 millimeters and depth of 80 millimeters. A diaphragm expansion chamber 113 millimeters in diameter is attached at its base. The card clears the lubber-line at the back of the bowl by approximately 10 millimeters. The observation glass, held by a verge ring with rubber gasket, caps the bowl and a hinged cover serves as a protection for the glass.

The inner bowl above described is suspended upon four corrugated shock-absorbing springs held inside a surrounding brass housing-cylinder approximately 200 millimeters in diameter. The space between outer and inner bowl is packed with horsehair intended as a shock-absorbing medium. The outer bowl is provided with lugs for mounting.

The instrument has a period of approximately 25 seconds and weighs about 7 pounds.

69900—22——5

R. A. F. PILOT'S COMPASS, MARK II.

The compass shown at the right of figure 9 is a liquid-damped vertical card instrument known as the R. A. F. Pilot's Compass, Mark II. The circular metal frame holding the vertical celluloid card ring (68 millimeters in diameter and 17 millimeters in height) is attached to the float chamber by means of four light L-shaped spokes which also act as damping vanes. The card divisions are marked upon the interior surface of the ring and "back readings" are taken with reference to a vertical curved wire attached at the back of the bowl which serves as a lubber-line. An agate pivot is mounted at the center of a recessed cavity in the lower float surface and rests upon a sapphire cup mounted upon a suitable bearing post. The pivot is prevented from leaving the cup, when the compass is in extreme positions and under conditions of excessive vibration, by means of a light wire arm extending from the interior wall of the bowl to within a very short distance from the top center of the float.

With a view to reducing errors in turns due to swirling of the compass liquid, the bowl of the R. A. F. Pilot's Compass is made as nearly spherical as possible. In order to completely carry out this feature the interior surface of the observation glass is concaved on a radius equal to that of the bowl proper. This has the disadvantage of reducing the apparent size of the card, when viewed through the glass, because of the lens effect caused by the concavity. This difficulty is overcome to some extent by the use of a damping liquid (zylol) possessing a high refractive index. The cover-glass has a diameter of 78 millimeters, slopes backward from the lower side at an angle of about 55° from the vertical, and is held in place by an ordinary bezel ring with rubber gasket at the joint. A miniature lamp mounted upon the bezel in a shielding socket illuminates the interior of the bowl. A flexible diaphragm 100 millimeters in diameter covers the expansion chamber attached below the bowl; the expansion chamber communicates with the bowl through two small holes in the spherical wall. Two filler plugs are provided at the top of the bowl.

FIG. 9.—R. A. F. pilot's compass, Mark II. Air compass, Mark II (quick period).

The bowl is mounted in a protective housing by means of four lugs which rest upon felt washers to relieve vertical shocks. Four strips of phosphor bronze attached to the sides of the bowl with their extremities touching the inner surfaces of the housing case react against vibrational motion in a horizontal plane.

The compensating device extends beneath the bowl and consists of two vertical series of horizontal tubes (one series fore-and-aft and the other athwartships) in which the correcting magnets may be placed. The latter are prevented from slipping out by a cylindrical sleeve which surrounds them.

Inasmuch as this instrument was designed to be free from the northerly turning error, characteristic of quick-period instruments, it is heavily damped and has a long period of swing varying in different models between 40 and 60 seconds, 54 seconds being a common value. The weight of the compass is about 4.9 pounds.

AIR COMPASS, MARK II (QUICK PERIOD).

The air compass, Mark II (quick period) shown at the left in figure 9 is identical with the R. A. F. Pilot's Compass, Mark II, described above, insofar as the bowl and mounting are concerned. The magnetic system and compensating device differ materially, however.

The magnetic system somewhat resembles that employed in the Creagh-Osborne 5/17 instrument and is so light as to require no float. The card has the form of a truncated cone with a diameter at the bottom of 51 millimeters tapering upward to a diameter of 63 millimeters at the top. This conical surface of thin sheet brass bears the card markings and has a height of 10 millimeters measured along a generating element. It is attached to the pivot hub by four brass wires. The pivot is of agate and rests in a sapphire cup mounted upon a bearing post similar to that of the instrument above described. The two bar magnets, 50 millimeters in length, are suspended below the card (30 millimeters between centers) upon light wires. The rotating system is prevented from lifting off the bearing by a wire retaining-arm similar to that used in the R. A. F. pilot's compass.

The compensating device is mounted above the card and consists of two brass tubes (one fore-and-aft, the other athwartships) of sufficient diameter to allow several correcting magnets to be inserted. The latter are prevented from falling out by a rotating brass sleeve held in position by a thumb nut.

This instrument is rather heavily damped but has a much shorter period of swing than the pilot's compass. The disposition of the compensating device makes it better adapted to mounting on certain planes. The weight of this instrument is approximately 4.9 pounds.

CAMPBELL-BENNETT APERIODIC COMPASS, TYPE 6/18, MARK II.

Among the most interesting of the more recent compasses is that developed by G. R. C. Campbell and G. T. Bennett, of the Admiralty Compass Observatory, Slough, England, and known as the aperiodic compass (figs. 10 and 11). With instruments of the ordinary type, a deflection of the rotating system from its position of rest is followed by a motion of oscillation of the system. In cases where the damping coefficient is small, the oscillation continues for some time on either side of the equilibrium position with ever diminishing amplitude.. By increasing the damping coefficient, however, it is possible to make the motion "aperiodic," i. e., the system returns to equilibrium without oscillation. The Campbell-Bennett compass is designed to possess this characteristic. The following description is intended to give an idea of the important features of the instrument:

FIG. 10.—Campbell-Bennett aperiodic compass, Type 6/18, Mark II.

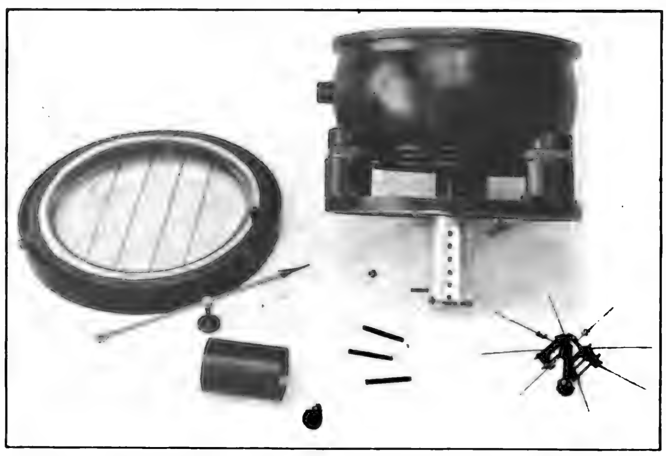

FIG. 11.—Campbell-Bennett aperiodic compass, Type 6/18, Mark II.

Referring to figure 11, the rotating element is seen to consist of a "spider" of eight wires radiating from a main hub member at the center of which the agate pivot is mounted (pivot point is in the plane of the wires). These wires are of brass or copper, have a diameter of

approximately 0.47 millimeter, and extend along the radii of a circle approximately 90 millimeters in diameter. The wires are equally spaced. Sheet-metal letters attached to the proper wires designate the cardinal points. The six bar magnets are suspended in suitable frames below the "spider," three at either side of the pivot. The end pieces of the suspension frames supporting these magnets are triangular in shape and hold each set of three magnets so that the individual bars are approximately 7 millimeters between centers. The object of a rotating element constructed in this way is obviously to bring about the condition of high damping resistance without appreciably increasing the moment of inertia of the system.

The pivot of the rotating element rests upon a sapphire cup held at the top of an adjustable bearing post, which is mounted centrally upon a bridge member spanning the diaphragm expansion-base of the bowl. The jewel cup itself rests upon a small piece of cork which acts as a cushion. In one of the models (fig. 10) the pivot is prevented from leaving the cup bearing by means of a flanged ring attached to the bearing post and overhanging a smaller ring forming part of the magnet frame. In a second model (fig. 11) a hood-shaped member extends downward directly above the center of the rotating element from a wire bridge forming the lubber-line and spanning the top of the bowl.

The bowl is of brass, cylindrical in form, and has a depth of 52 millimeters and a maximum inside diameter of approximately 136 millimeters. A miniature electric bulb is attached at one side and projects its rays through a ground-glass window in the side so as to illuminate the interior of the container. A filler plug is provided at one side. In addition to the expansion base a series of three diaphragm boxes to care for liquid expansion is attached underneath the bowl. The bowl is covered by a glass crystal 117 millimeters in diameter which is surmounted by a rotatable bearing plate with four parallel wires extending in a north-south direction and spaced approximately 20 millimeters apart. The bearing plate is graduated in 2° intervals, with each 10° interval numbered and with the cardinal points lettered.

Three lugs spaced at equal angular intervals around the base of the bowl rest upon shock-absorbing washers of fibrous material mounted upon cylindrical hollow pedestals screwed to a circular base casting of aluminum. The above-mentioned shock-absorbing washers care for vertical vibrations, while spiral brass springs inside the cylindrical pedestals are attached to bolts from the mounting lugs so as to relieve horizontal vibration. A vertical compensating pillar threaded into the base is drilled with two series of holes (one fore-and-aft, the other athwartships) in which the small compensating magnets may be placed at suitable distances from the magnetic element to provide the necessary compensation. A brass sleeve slides over the compensation tube and serves to hold the magnets in place.

The instrument as described weighs 6 pounds. It requires about 15 seconds for the magnetic system to come to rest after a deflection of 45° from the equilibrium position.

DESCRIPTIONS OF FRENCH COMPASSES.

AÉRONAUTIQUE MILITAIRE COMPASS—NONCOMPENSATED TYPE.

The Vion Aéronautique Militaire compass (fig. 12) is of the noncompensated type. This instrument is liquid damped (alcohol mixture) and has a horizontal card. The latter, in the form of a ring of composition material resembling hard rubber, has a diameter of 70 millimeters and bears luminous markings at 10° intervals, with numerals of luminous material at the 30° points. The letters marking the cardinal points are also luminous. The card is carried on a float chamber with two magnets inclosed in brass tubes attached to the under surface. The hardened alloy pivot is mounted upon a bridge member spanning the diaphragm expansion base of the bowl, while the sapphire cup is set in a recessed cavity in the lower surface of the float. The diaphragm base is protected from mechanical injury by a metal cap which covers it.

The bowl has a depth of 46 millimeters and an inside diameter of 92 millimeters, thus allowing a clearance of 11 millimeters between the card and the wall of the bowl. A lubber-line is suitably mounted in the bowl. A tapped and plugged filler hole in the side allows for replenishment of the liquid when leakage occurs or bubbles form. A nickeled rim divided in degrees and properly marked surmounts the bowl. An adjustable index sliding along the rim is provided for the convenience of the pilot in setting his course.

The suspension of this instrument is by means of gimbals and an ordinary yoke mounting bracket. The compass is constructed largely of brass and weighs about 3.3 pounds. It has a period of approximately 17 seconds and damping constant of 9.

AÉRONAUTIQUE MILITAIRE 1 COMPASS—COMPENSATED TYPE.

The Aéronautique Militaire 1 compass (fig. 13) is one of the most recent of the French instruments. It is of the liquid-damped (alcohol mixture), horizontal-card type. Vertical reading is made possible by use of the prism seen in the illustration.

The card, in the form of a mica ring 75 millimeters in diameter, bears two sets of divisions, one set erect for direct reading and the other set inverted and reversed for observations through the prism. The divisions for direct reading are spaced at 5° intervals with numerals at the 20° points, while the divisions for prism readings are spaced at 2½° intervals with numerals at the 10° points. The cardinal points are marked with luminous letters.

The card is mounted on a float chamber of usual design with two magnets attached to the lower surface as in the instrument previously described. This compass differs from the former

FIG. 12.—Aéronautique militaire compass, noncompensated type.

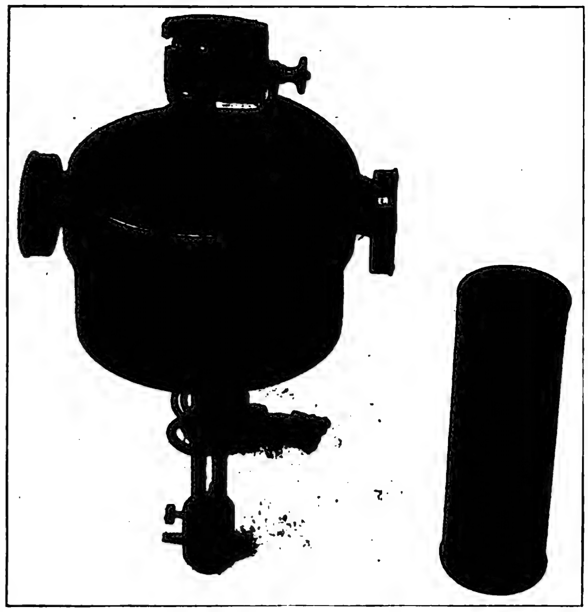

FIG. 13.—Aéronautique militaire 1 compass, compensated type.

Vion instrument, however, in that the pivot (jewel in brass stem) of this model is mounted in a recessed cavity in the lower float surface, while the cup of the former type was carried by the float. The jewel cup is held upon a rubber cushion in a socket upon a bearing post mounted at the center of the bowl base.

The bowl has a depth of 37 millimeters and an inside diameter of 106 millimeters. A shelf extending from the wall of the latter bears the luminous lubber-line. A nickeled rim divided in degrees and properly marked surmounts the bowl and observation glass. An adjustable index sliding inside the rim is provided for the convenience of the pilot in setting his course. A filler hole passes through the bowl base and at one side of the latter a ground-glass window is set directly above a miniature lamp held in its socket upon a protective cover plate just below the base. This plate which is screwed to a ring extension of the bowl also covers the diaphragm expansion chamber with which the instrument is equipped.

A vertical slotted compensation column fastened centrally upon the protective cover plate carries two adjustable sliding collars in which the correcting magnets are secured. This compensating device is covered by a tube threaded to a collar on the cover plate.

The compass bowl rests in a mounting ring provided with two hubs which are supported upon rubber shock-absorbing disks fixed upon the arms of a yoke mounting-bracket.

The compass as described has a period of approximately 16 seconds and a damping constant of 7.5. Its weight is approximately 6 pounds.

MAUVE COMPASS—NONCOMPENSATED TYPE.

The Mauve noncompensated compass (fig. 14) is of the liquid-damped (alcohol mixture) horizontal-card type. The card, having a diameter of 55 millimeters, marked with nonluminous material and with circumferential divisions placed at 5° intervals, is carried by a small float member. The sapphire bearing cup is set in a small recessed cavity at the under side of the float and rests upon a hardened alloy pivot mounted centrally upon a bridge member extending across the bottom of the bowl. Two bar magnets 50 millimeters in length and attached to the underside of the float serve as magnetic elements.

FIG. 14.—Mauve compass, noncompensated type.

The bowl is hemispherical (90 millimeters diameter) with an expansion diaphragm base. A tapped and plugged filler hole passes through the side of the bowl. No fixed lubber-line or graduated bowl rim is provided, but a small adjustable index slides in a circular path above the crystal to any desired setting.

The bowl is suspended by means of six coiled wire springs, three at either side of the instrument and attached at the extremities of a brass yoke-shaped mounting-bracket.

The instrument described weighs 1.7 pounds, has a period of approximately 25 seconds and a damping coefficient of 10.

MAUVE COMPASS—COMPENSATED TYPE.

The Mauve compensated compass (fig. 15) is liquid damped (alcohol mixture) and so constructed that the card may be directly read either horizontally or vertically. The top or horizontal card surface of the cylindrical float, upon which the luminous graduations are marked at 10° intervals against a black background, has a diameter of 70 millimeters. The cylindrical vertical card surface of the float 18 millimeters in height bears similar markings to be observed through the opening in the side of the bowl. The two cylindrical magnetized bars approximately 60 millimeters in length are suspended 26 millimeters between centers at the lower side of the float. The latter carries in a suitable cavity a sapphire cup and is supported by a hardened alloy pivot upon which the cup rests.

FIG. 15.—Mauve compass, compensated type.

The vertical surfaces of the sheet brass cylindrical bowl serve as a protective housing for a heavy glass ring ($3\frac{1}{2}$ millimeters in thickness, 40 millimeters in height, and with an inside diameter of 86 millimeters) which surrounds the card. This ring rests on a gasket at the bottom of the metal bowl and is closed at the top by the glass crystal which also rests on a suitable gasket rendering the joint free from leaks. The card is visible through the glass ring which is exposed to view at either side through an opening in the protective bowl housing. The corrugated expansion base of the bowl is also covered by this housing and the filler hole is tapped and plugged in the base. The bowl is provided with a rim divided in degrees along which a sliding index and index bar are adjustable as desired by the pilot.

The vertical cylindrical compensating shaft 150 millimeters long is mounted centrally at the base of the bowl and has two sliding blocks each carrying two compensating magnets vertically adjustable upon it. The compensating device is covered by a protective cap of aluminum held in place by a hex-nut threaded to the lower extremity of the compensating shaft.

The mounting bracket of aluminum is yoke shaped and is fastened to the bowl by means of four brass springs at each side.

The instrument weighs approximately 2.4 pounds, and has a period of about 24 seconds.

FIG. 16.—De Vries and Courbet compass.

DEVRIES AND COURBET COMPASS.

The DeVries and Courbet liquid-damped (alcohol mixture) compass (fig. 16) is of the combination horizontal and vertical card type. The horizontal surface of the float (55 millimeter diameter) is marked at 10° intervals with luminous material, while the cylindrical vertical surface (13 millimeters height) bears similar markings which may be viewed from either side of the bowl through the glass ring which serves as a part of the liquid container. A luminous lubber-line consisting of a wire of small diameter is placed at the center of the observation opening. The float is of the usual form for this type of compass and is mounted upon a hardened alloy pivot extending upward from a bridge member above the expansion bowl base to support the sapphire cup member of the float.

The glass crystal caps the glass ring container (70 millimeters inside diameter), the joint being made tight by a suitable gasket. A second gasket is provided at the base of the bowl to serve as a seat for this ring. Two adjustable circular sliding indices 180° apart are provided for the use of the pilot in course setting.

FIG. 17.—The "Monodep" compass.

The protective bowl housing surrounding the glass container ring is of sheet metal and has two hubs attached diametrically opposite each other by which the instrument is suspended. These hubs carry at their outer extremities the shock-absorbing suspension devices, each of which consists of four small compression springs radiating at 90° intervals from the hub and attached in the circular openings found at the extremities of the aluminum yoke-shaped mounting bracket.

This instrument is provided with a device intended for compensation. It consists merely of a short brass tube attached to the base of the bowl and slotted to hold the small compensation magnets in position along two axes 90° apart. The compensation tube has a threaded section at its lower extremity and a knurled cap is supposed to draw the slotted sections of the tube together and thus to clamp the magnets in place. The amount of compensation is regulated by the number, length, and location of magnets used.

This instrument weighs 1.7 pounds and has a period of approximately 15 seconds.

THE "MONODEP" COMPASS.

The "Monodep" dry or air damped compass (fig. 17) has several interesting features which deserve mention. In place of the usual cylindrical shaped magnetic elements, this instrument is equipped with two very thin magnetized plates mounted parallel to each other, with flat surfaces vertical, upon a vertical spindle with lower jewel pivot bearing. The card is also mounted a short distance below the upper extremity of the spindle and the latter is supported

near its upper end by a brass frame secured to the compass bowl. The spindle carries at its upper end above the card a small pinion which mates with the second pinion of a train of four small gears connecting with a small spindle holding a horizontal rotating arm with a black circular disk at its extremity. The gear train multiplies any motion of the magnetic element and card relative to the bowl so that the circular disk index executes a movement just four times as great as that of the card. In this manner the movements of the magnetic element are magnified so that greater precision may be obtained in the compass readings.

The card is 65 millimeters in diameter, divided into 360° and with no figures or letters except those at the cardinal points and a red star to mark the north point.

The brass frame upon which the mechanism is mounted is securely fastened into an aluminum alloy bowl with a glass top surmounted by a circle divided into 90 equal parts marked at 10° intervals from 0 to 90°. The bowl is swung in gimbals with a suitable yoke shaped mounting bracket of aluminum alloy.

Mounted at the center of the glass top is a cylindrical brass box containing the reduction train which accounts for the motion of a transparent celluloid pointer with a star at its extremity underneath the glass. This celluloid pointer moves through an angle of 90° when the brass index-blind pointer to which it is connected above the glass is moved by the pilot through an angle of 360°. The compass is so constructed that one of the cardinal points of the card lies opposite the lubber-line when the index points to the 0-90° point of the exterior divided circle of the instrument.

FIG. 18.—Favé air damped compass.

In establishing a definite compass course the brass pointer is turned until the star on the celluloid pointer holds a position directly above the place which the north marking of the card should occupy. The brass index-blind pointer will then be in a position directly over the circular disk index. Any deviation from this setting will be shown by a movement of the index equal to four times the movement of the card. It is thus seen that the pilot, in reading his compass, notes the quadrant in which the star or north point on the card is located and reads from the exterior divided circle the exact point indicated by the index and the brass marker which is directly above it.

The instrument, complete, weighs 1.2 pounds.

FAVÉ AIR-DAMPED COMPASS.

This compass (fig. 18), conceived by the French hydrographic engineer Favé, is without a doubt one of the most beautiful and delicate examples of the instrument makers' art. It is of the dry or air damped type and is designed for service on lighter-than-air craft.

The main rotating element is made up of a skillfully formed and balanced spider of slender drawn glass or quartz threads radiating from a central hub upon which the magnetic element is mounted. The threads radiate as generatrices of three different surfaces. The first is a horizontal plane surface (150 millimeters in diameter) in which the 12 bar magnets are also fixed in a suitable frame. The second surface is that of a cone with its apex near the bearing and with an apex angle of approximately 60°, while the third surface is also that of a cone with its apex similarly placed, but with an apex angle of approximately 30°. The threads of the three surfaces are held in place by other threads forming circular rings and attached to

the element threads by minute beads. This system moving in the surrounding air furnishes the damping effect.

One element of the horizontal surface lying parallel to the magnets, and thus along the meridian, is more rugged than the others and has the point and tail of an arrow attached at the respective extremities of the spine and pointing toward the north and south magnetic poles. This rotating system is mounted on a jewel bearing (jewel cup on card, alloy pivot on post) at the center bearing post, which is provided with a device similar to that found in transit compasses for lifting the rotating part when not in use from its bearing and against a guide rod extending from the crystal. This lifting device is operated by a knurled thumb nut mounted at the side of the case. The N–S element of the system extends to within about 1 millimeter from a horizontal annular disk attached to the sides of the bowl and bearing the scale divisions marked by degrees from 0 to 360.

The bowl, which is covered by a glass crystal, has an inside diameter of 178 millimeters and depth of 100 millimeters. The instrument is mounted in gimbals as shown. It weighs 5.4 pounds, has a period of 9 seconds, and a damping coefficient of 5.

DESCRIPTIONS OF GERMAN COMPASSES.

KAISERLICHE MARINE KOMPASS.

The Kaiserliche marine kompass (fig. 19) has a horizontal card (100 millimeters diameter) on a cylindrical float 65 millimeters in diameter and 19 millimeters deep. A jewel cup mounted

FIG. 19.—Kaiserliche marine kompass.

in a cavity in the lower surface of the float rests upon an alloy pivot on a spring supported by a bearing post extending from a bridge member at the base. Two flat bar magnets are attached at the bottom of the float. The card is graduated in 5° intervals with distinctive markings for the cardinal points. On the inner surface of the bowl are four black lines (on white) at 90° intervals. These lines are repeated as white marks on the outer ring which holds the glass in place.

The bowl is cylindrical (135 millimeters in diameter and 65 millimeters deep) and contains alcohol as a damping liquid. At the bottom is a weighted cap carrying a small electric lamp at its center. The base of the bowl is formed by a corrugated metal expansion diaphragm. In the center of this diaphragm is a circular glass window through which light from the lamp enters the bowl. Internal reflection in the bowl provides sufficient illumination for the face of the card.

A unique feature of the instrument is an index pointer mounted on the card, which may be set from the outside. A plunger, with a knob on the outside and a cogged disk on the inside end, is held in a packing box through the center of the glass. By pressing down on the knob, the cogged disk is engaged in a similar disk on the pointer. At the same time a stiff spring under the pivot is compressed and the float is lowered until a cogged rim around the cup engages

a similar ring on the pivot support. Then the pointer may be set by turning the knob while the card remains stationary.

The bowl is hung in heavy gimbals mounted in a yoke which is pivoted so as to be adjustable upon the supporting bracket. The yoke carries an index line and a clamping screw, and the bracket a scale marked from +10 through 0 to −10. The slotted compensating magnet column extends downward from the supporting bracket to which it is attached and has two sliding collars adjustable vertically for holding the correcting magnets. A detachable sheet-metal cover protects the compensating magnets.

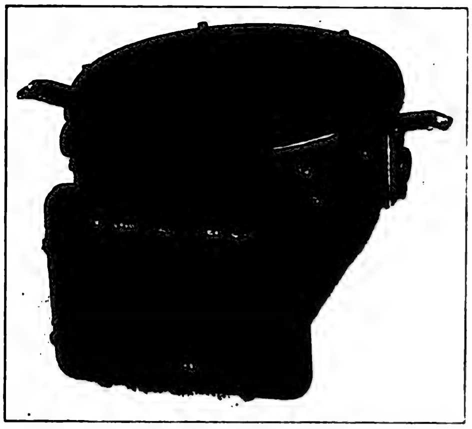

FIG. 20.—Ludolph armee kompass I.

The period of this instrument is about 25 seconds. Its weight is 6.4 pounds.

LUDOLPH ARMEE KOMPASS I.

The Ludolph compass (fig. 20) is of the liquid-damped (alcohol mixture) type. The float is cylindrical in shape, about 70 millimeters in diameter and 35 millimeters in depth, and bears a beveled projecting rim around the lower edge. Four magnets in the form of cylindrical rods are attached at the bottom of the float. The upper face, forming the horizontal card, is graduated in 10° intervals with the cardinal points marked and lettered. The vertical face of the float bears two identical scales graduated at 5° intervals from 0 to 360. The lower scale is on the beveled rim and the upper scale is separated from it by a colored band, red for the north and blue for the south half of the scales. The pivot, which is of alloy, is supported by a small brass post at the bottom of the bowl. A sapphire cup is set in the float.

The bowl is hemispherical in shape (about 120 millimeters in diameter and 80 millimeters in depth) with a rectangular projection at the side, 70 millimeters wide and 50 millimeters deep, which is covered by a glass observation window. At the bottom of the bowl is a metal diaphragm chamber to compensate for expansion of the damping liquid. A filling hole with a threaded plug, and a small circular window over which a lamp may be attached are found on the bowl. The horizontal face bears a scale around the rim graduated at 5° intervals, and at the center of the glass is pivoted a metal pointer. The inside of the bowl is painted white and bears two lubber-lines, a black mark for the horizontal face of the card and a black wire for the vertical face.

No provision is made for attaching compensating magnets. Two small angle brackets at the top of the bowl are used for mounting the compass. The compass weighs 2.9 pounds.

The Ludolph armee kompass II is similar to the instrument just described but is somewhat larger. The bowl is about 135 millimeters in diameter and 90 millimeters in depth.

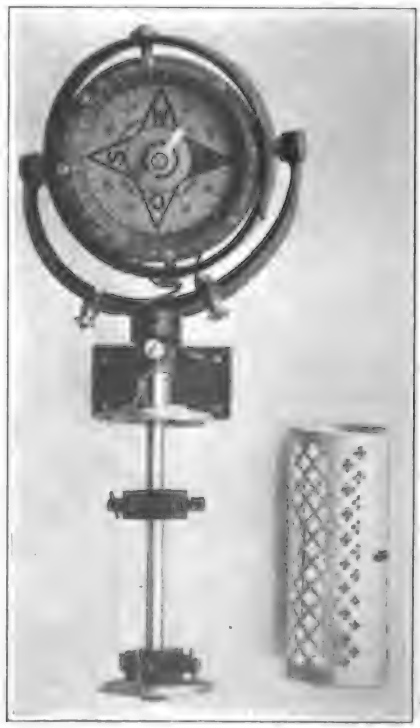

FIG. 21.—Sendtner armee kompass III.

SENDTNER ARMEE KOMPASS III.

The Sendtner armee kompass III (fig. 21) is of the liquid-damped (alcohol mixture), horizontal-card type. The card (85 millimeters diameter) graduated in 10° intervals is carried by a float of usual design. The cardinal points of the card are distinctively marked and let-

tered. Numerals are found at the 30° points. An alloy pivot is carried in an indented cavity in the lower surface of the float while the jewel cup upon which the pivot rests is supported upon a post with spring shock-absorbing cup socket at its upper end. The magnetic elements are sealed inside the float chamber.

The bowl is cylindrical, 115 millimeters in diameter and 60 millimeters deep. A metal pointer, pivoted at the center of the glass, may be set to any desired angle as indicated by a scale graduated at 10° intervals on the rim of the bowl. The interior of the bowl is painted white and bears four black lubber-lines under the 90° points of the exterior scale. The base of the bowl is formed by a metal diaphragm in the center of which is set a ground-glass window. A heavily weighted cap containing an electric lamp covers the base. Two flexible wires from the lamp lead to binding posts on the supporting yoke.

The gimbal suspension of the bowl is mounted in a yoke which is adjustable upon the bracket support. A grooved compensation column with adjustable sliders holding the correcting magnets is mounted below the bracket.

This instrument has a period of approximately 25 seconds. Its weight is 4.8 pounds.

PFADFINDER ARMEE KOMPASS III.

The Pfadfinder armee kompass III (fig. 22) is of liquid-damped (alcohol mixture) type with a horizontal card. The card (84 millimeters in diameter) is graduated at 10° intervals, with distinctive markings for the cardinal points. It is fastened to a float to which are attached two bar magnets incased in copper tubing. An alloy pivot on the float rests in a jewel cup set on the end of a bearing post attached to a spider at the bottom of the bowl.

Fig. 22.—Pfadfinder armee kompass III.

The bowl is about 120 millimeters in diameter and 70 millimeters deep. Its base consists of a metal diaphragm covered by a weighted cap. A rim graduated at 10° intervals is set around the glass face of the bowl. In this rim is also a lamp socket. At the center of the glass is pivoted a movable pointer. The interior of the bowl is painted white with four black wire lubber-lines set under the 90° points of the exterior scale.

The bowl is suspended in a gimbal ring mounted upon a yoke bracket support. To this bracket is also attached the compensation column carrying the correcting magnets in sliding collars of the usual form. A protective case surrounds the compensating device.

This instrument weighs 5.5 pounds.

PFADFINDER ARMEE KOMPASS IV.

The Pfadfinder armee kompass IV (fig. 23), a liquid-damped (alcohol mixture) compass, has a combination horizontal and vertical card. The float with card markings upon it is cylindrical and about 70 millimeters in diameter by about 23 millimeters in depth. The magnetic elements are sealed inside the float chamber. The horizontal face bears graduations at 10° intervals, with special markings and letters for the cardinal points. The vertical face is beveled from each edge inward toward the center. Upon this face are two identical scales graduated at 10° intervals from 0 to 360°. The scales are separated by a colored band, blue from the 0 to the 180° scale divisions and red for the remainder. The bearing is formed by an alloy pivot attached in a cavity in the lower float surface and resting upon a sapphire cup supported by the usual form of bearing post with spring shock-absorbing socket.

The cylindrical bowl is 105 millimeters in diameter and 85 millimeters in depth. The bottom is formed by a diaphragm expansion covering. On the curved surface of the bowl are a filler hole with threaded plug, and a window for viewing the vertical face of the card. The horizontal glass observation window is held in place by a metal ring graduated from 0° to 360° at 10° intervals. This ring also contains the lamp socket. A movable pointer is pivoted at the center of the glass. The inside of the bowl is painted white. Two black wires, 180° apart, serve as lubber-lines for both faces of the card.

The support consists of a bracket, one end of which is formed into a circular plate with a clamping ring by which the compass bowl is held in place. On the lower side of the plate an aluminum bar projects, holding the compensating magnets. An aluminum case protects these magnets. There are two binding posts on the bracket, connected by wires to the lamp socket.

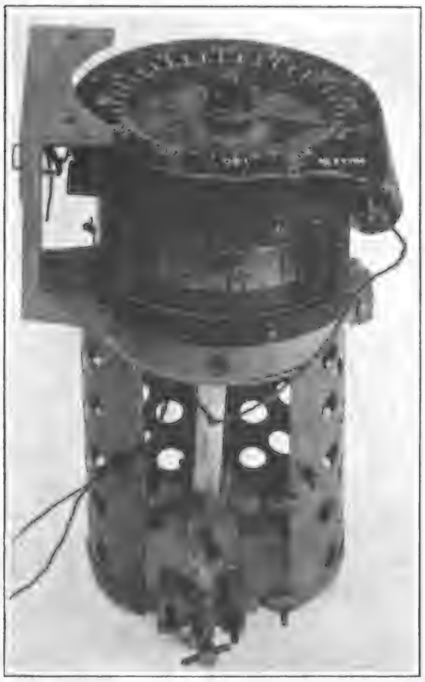

FIG. 23.—Pfadfinder armee kompass IV.

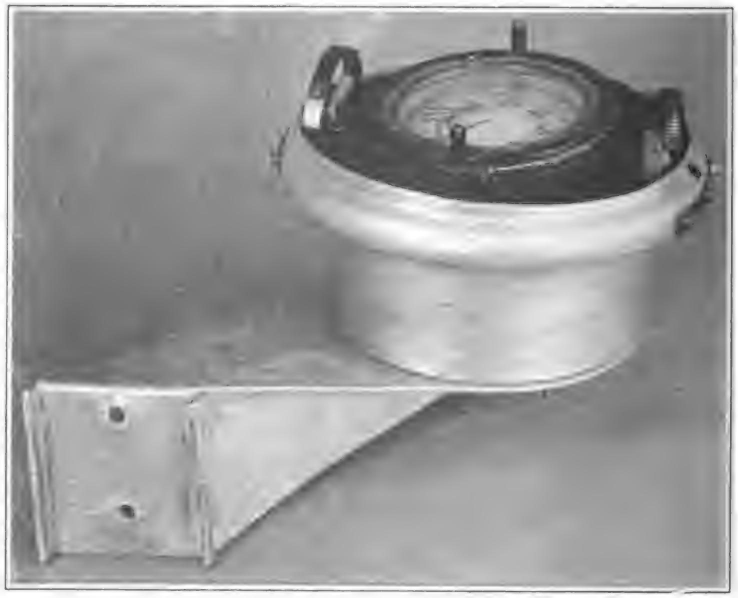

FIG. 24.—Pfadfinder kompass für aviatik.

This instrument has a period of approximately 25 seconds and weighs 3.2 pounds.

PFADFINDER KOMPASS FUR AVIATIK.

A compass of the liquid-damped type is illustrated in figure 24. The unusual form of bracket is used to mount the compass upon a vertical member of the airplane structure remote from disturbing magnetic influences. The instrument may be mounted in the wing, as shown in figure 25. The support consists of a large aluminum bracket carrying an aluminum bowl. The gimbal ring, in which the compass is swung, is hung in this bowl by means of spring suspensions, which can be clearly seen in figure 24.

The horizontal card is 73 millimeters in diameter and is graduated at 5° intervals. The cardinal and 45° points are marked by black triangles, with the exception of the north point, which is marked by a red arrow. The card is attached to the top of the float, in which are mounted two magnets. A sapphire cup on the float rests on an alloy pivot, which is supported from the base of the bowl. Alcohol is used as the damping liquid.

The compass bowl is cylindrical, about 110 millimeters in diameter and 75 millimeters deep. The base is formed by a metallic diaphragm pierced by a hole which connects the bowl with a flat expansion chamber of corrugated metal. A heavy lead disk forms a protecting cap. At one side of the bowl is a filling hole stopped by a threaded plug.

The face of the bowl shows an interesting departure from the usual practice. A fixed glass carries the lubber-line, a black radial line which is continued down on the inside of the bowl. Above the fixed glass is a second glass set in a brass ring, which is graduated in single degrees from 0 to 360. A red radial line extends from the center of this glass to the zero point of the scale. Glass and ring may be turned as a unit by means of two brass knobs on the ring. Outside of the movable ring is a metal ring, carrying an index mark directly over the lubber-line. This ring may be clamped by means of two screws with long projecting heads set 90° away from the index mark. Clamping this ring also clamps the movable ring.

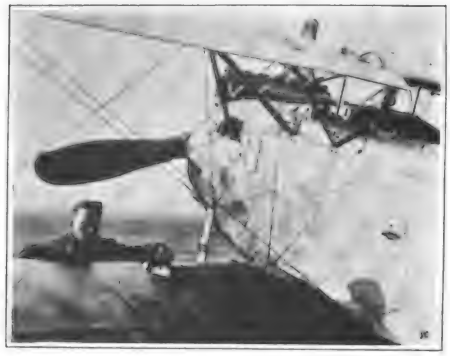
FIG. 25.—Wing mounting of compass.

This instrument has a period of about 25 seconds. It weighs 4.9 pounds with the mounting bracket.

REMOTE INDICATING AND REMOTE CONTROL COMPASS.

Among the most interesting of foreign aircraft instruments is the Bamberg remote indicating and remote control compass (figs. 26 to 31, inclusive). In this compass arrangement we find an ingenious design in which difficulties due to disturbing magnetic influences from the motor and elsewhere are avoided, by locating the magnetic compass element at a position remote from these conditions which ordinarily present such a serious obstacle to the proper functioning of the instrument. Intended for use on the larger types of aircraft, the Bamberg compass system serves as a means of control between the navigator or observer and the pilot whose position in the aircraft may be at some distance from the navigator's station.

The magnetic compass.—The magnetic compass upon which the system depends for its indications is a comparatively heavy liquid-filled type mounted in gimbals and having a period of 25 seconds. The compass bowl has an inside diameter of 145 millimeters and is equipped at its base with an expansion chamber consisting of two flexible metallic diaphragm boxes.

The magnetic element is of the float type, but instead of a card graduated in the ordinary manner it carries a metal disk cut in such a shape as to act as a blind in regulating the passage of rays of light projected upward from the base of the compass bowl by two 8-volt electric lamps attached diametrically opposite each other (figs. 28 and 30). The light rays from each

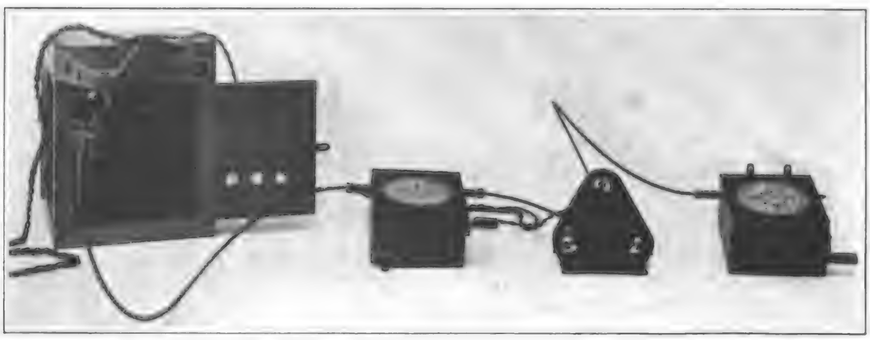
FIG. 26.—Remote indicating and remote control compass. (Complete outfit.)

lamp are focused by a lens upon a corresponding selenium cell incased in a water-tight bridge member which spans the top of the bowl (figs. 28 and 30). The lamps are made adjustable in their sockets to allow for varying their distance from the lenses.

Selenium cells.—These selenium cells have the property that their electrical resistance varies with changes in the intensity of the light which falls upon them. Thus, with the magnetic element carrying the blind in a certain position relative to the bowl, both light cones are eclipsed and the two selenium cells remain in darkness. If, however, the compass bowl is rotated

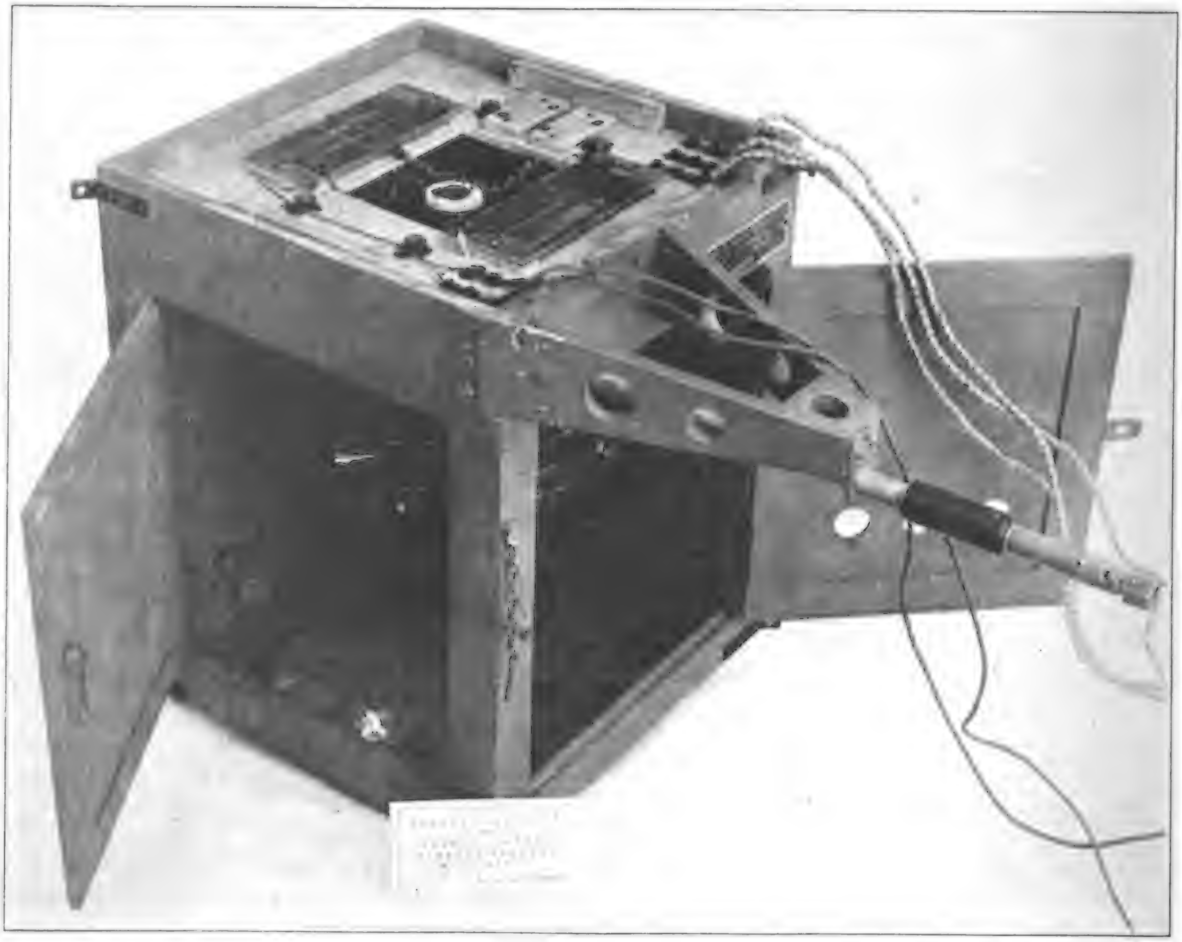

FIG. 27.—Remote indicating and remote control compass. (Magnetic compass in housing.)

FIG. 28.—Remote indicating [illegible] [illegible]te control compass. (Magnetic comp[illegible] [illegible] housing.)

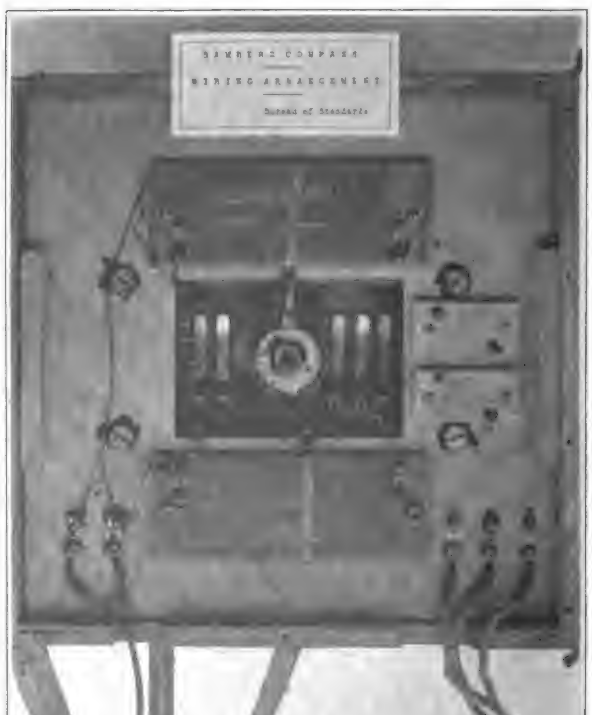

FIG. 29.—Remote indicating and remote control compass. (Wiring arrangement.)

through a certain angle, one of the light cones remains eclipsed while the other is uncovered so that its rays fall upon the selenium cell above it. This lowers the resistance of the illuminated cell by an amount which is dependent up to a certain limit (when one light becomes completely uncovered) upon the angle through which the compass bowl has been turned relative to the magnetic element.

The selenium cells form two arms of a Wheatstone bridge, the remaining arms consisting of resistances wound upon slate cards (figs. 29 and 31). Current is supplied either from a battery or a direct current wind-driven generator. A small deviation from the indicated course unbalances the bridge, which is indicated to the pilot by the deflection of the bridge galvanometer located in the pilot's cockpit.

Course indicator or control box.—The navigator is equipped with a course indicator or control box (shown in fig. 26) which he uses in controlling the direction of flight. The pilot (as well as any other occupant of the aircraft) may also be equipped with one of these indicators. The mechanism is inclosed in a small wooden box with a glass window in its upper side, through which the pilot or navigator observes a dial graduated with a scale similar to an ordinary compass card. A black lubber-line is painted on the glass for use as a reference point. The mechanism consists simply of a train of gears which connect a hand crank to the dial and also to a spindle equipped with connections for flexible shafting. The gear ratio is such that one complete turn of the crank causes the flexible shafting spindle to make two complete revolutions while the indicating dial turns through an angle of 6°.

FIG. 30.—Remote indicating and remote control compass. (View of bowl, bridge, and resistance elements.)

Compass control.—The course indicators in the airplane are connected to each other and in turn to the compass itself by means of lengths of special flexible shafting, so that all the indicators are set simultaneously and in the same manner as the compass bowl itself.

The flexible shafting which extends back to the compass bowl is connected with the latter through a worm and mating gear (fig. 28), which function in such a manner as to cause the main yoke suspension of the compass bowl, which is integral with the worm gear, to rotate as the flexible shafting turns. The electrical connections from the movable elements of the compass are brought to the fixed elements through commutator rings with corresponding brushes as shown in figures 29 and 31.

Operation of the installation.—Let us first assume that the outfit is so installed in the aircraft that both selenium cells are in darkness when the indicators show the aircraft to be directed along the north and south magnetic meridian. In this position the bridge circuit will be balanced and the pointer of the pilot's galvanometer or steering gage (shown in fig. 26) will be in its neutral position. Any deviation from this north-south course will become apparent by a change in position of the pointer of the steering gage, which will turn clockwise or counterclockwise according to whether the heading of the aircraft changes to the right or to the left. Thus by watching this instrument the pilot is able to hold to the course.

Now, let us assume that the navigator wishes to change the course by an angle of 15°. By rotating the crank of his course indicator or control box until the dial shows a change of 15° in the desired direction he also turns the other indicators in the aircraft and at the same time the bowl of the compass. This causes one of the selenium cells (both cells turning with the bowl) to receive a greater illumination than the other, the balance of the bridge circuit is destroyed and the pointer of the steering gage before the pilot changes from its neutral position to a new position showing in which direction he must rudder in order to follow the new course. The amount of this turning is indicated roughly up to a certain degree (about 25° when one light is completely uncovered) by the angle through which the pointer turns.

In case an accident occurs so that the aircraft is out of control during a period long enough for it to assume a heading differing by 180° from that of the proper course, the pilot is able to

KEY TO WIRING DIAGRAM OF THE REMOTE INDICATING AND REMOTE CONTROL COMPASS.

(Refer to figure 31.)

A, B, G(3) } Connectors for battery or generator wires.
D, E } Connectors for pilot's steering gage.
F, G, H, K, L } Commutator connections leading to the rotating compass bowl so as to provide electrical connections between the illuminating elements, the selenium cells, and the stationary elements of the circuit.
R_1, R_3 } Resistances for controlling sensitivity of galvanometer.
R_2, R_4 } Bridge arm resistance coils.
S_1, S_2 } Selenium cells with common wire lead to K.
T_1, T_2 } Lamps supplying illumination to the selenium cells.

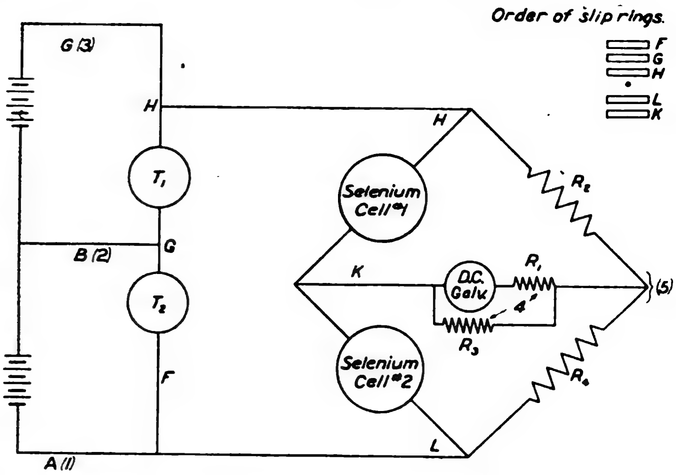

FIG. 31.—Remote indicating and remote control compass. (Wiring diagram.) See key to diagram.

recognize this fact even though the pointer of his steering gage is in a neutral position, for each turn of the aircraft to one side or the other is shown by the steering gage as a turn in just the opposite direction.

The weight of the system is as follows:

	Pounds.
Magnetic compass and bridge elements in protective housing	16.0
Two course indicators	8.4
Pilot's steering gage or galvanometer	1.8
Flexible shafting	.9
Total weight not including battery or generator	27.1

DESCRIPTIONS OF MISCELLANEOUS COMPASSES.

The foregoing descriptions of American and foreign compasses relate to representative instruments which have been developed and placed on the market for use on aircraft. In concluding this paper it may be of interest to mention briefly several of the instruments now in the process of development, as well as one or two types already produced but which do not logically come under the groupings as carried out in the first part of the paper.

EARTH INDUCTOR COMPASS.[1]

The following description relates to the earth inductor compass which was developed by Dr. Paul R. Heyl and Dr. Lyman J. Briggs of the Bureau of Standards at the request of, and with funds furnished by, the Engineering Division, Air Service, United States Army.

The application of the earth inductor to the determination of magnetic direction is not new. In magnetic survey work, use is made of both the earth inductor and the dip circle for

[1] The author is indebted to Dr. Briggs and Dr. Heyl for the above description of the Bureau of Standards earth inductor compass.

the determination of magnetic inclination or dip, with results of equal precision. A number of earlier attempts have been made to use the earth inductor as a compass, but no one of these proposed devices possessed sufficient practicability to bring it into use during the recent war.

In all previous attempts at the construction of a compass of this type the current developed in the rotating coil, amplified if necessary, was caused to pass through a galvanometer, and the course of the vessel judged from the amount of deflection produced. This instrument differs from all previous attempts in the following respects:

1. It employs a null method for its indications, and hence enjoys all the advantages of sensitivity characteristic of null methods as a class.

2. A course-setting device of a novel type is employed. By turning a movable dial at the instrument board the electrical connections of the distant revolving coil to the galvanometer are so arranged that the pointer reads zero only when the vessel lies in the desired course.

FIG. 32.—Earth inductor compass.

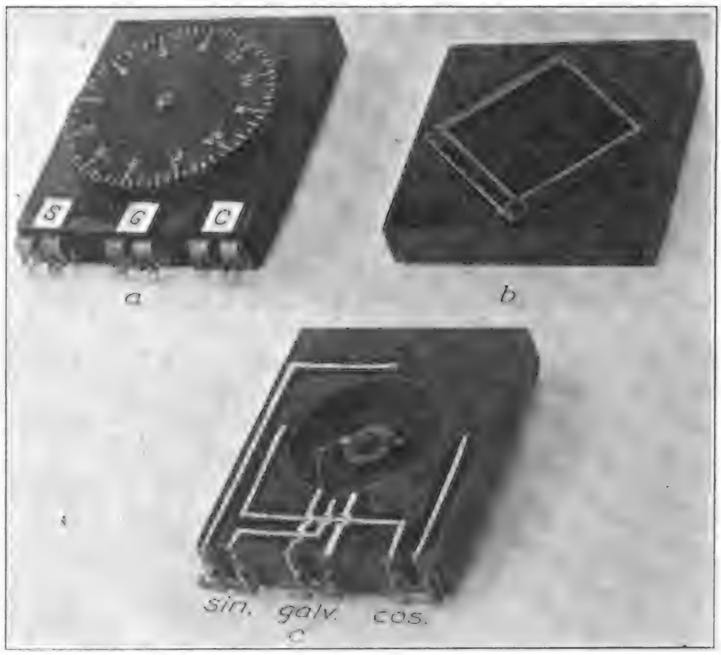

FIG. 33.—Earth inductor compass.

3. A method is provided for eliminating the errors due to rolling and pitching, arising from the action of the vertical component of the earth's field.

4. By the judicious use of iron in the core of the revolving coil the size of the apparatus may be sufficiently reduced to make it practicable of installation in an airplane.

Current is generated by the rotation in the earth's horizontal field of a cross-shaped armature 1 (fig. 32) rotating about a vertical axis. The vertical position of this axis is preserved during rolling and pitching by suspending it in the gimbal ring 2. In the case of installation in an airplane, power is applied to drive the armature by the cup propeller 3 acting through a section of flexible shaft 4.

A four-segment commutator and four collecting brushes, spaced at 90° takeoff current from the armature. The electromotive forces at the two pairs of brushes will be functions of the course followed by the ship. The setting of the brushes is so made that when the ship lies in a line making an angle Θ with the magnetic meridian, the electromotive forces at the brushes are $\sin \Theta$ and $\cos \Theta$.

Since, in general,

$$m \sin \Theta + n \cos \Theta = 0$$

if $\tan \Theta = -\frac{n}{m}$, the galvanometer reading may be made zero in any desired course by combining, additively or subtractively, suitable fractions or multiples of the voltages from the two pairs of brushes. This is done by the dial switchboard (fig. 33).

A movable dial (fig. 33, *a*) carrying compass graduations, has on its under side two wiping contacts, which connect with opposite diametral points of a square resistance frame (fig. 33, *b*). The sine brushes are connected to the upper and lower corners of this square and the cosine brushes to the right and left corners (fig. 33, *c*). The galvanometer leads are connected to the wiping contacts above mentioned through another pair of wiping contacts and the movable hub which carries the dial.

The mathematical theory of this device shows that if a circular resistance frame be used, the compass will be affected by an octantal error amounting at its maximum to about four degrees. By the use of a square resistance frame this error is eliminated.

The armature 1 (fig. 32) is wound on each arm with 500 turns No. 20 wire. The arms are connected in series as a closed coil winding. The brushes are of carbon. Experiment has shown that in a consecutive run of 146 hours such brushes suffer only trifling wear, and deliver the exact voltage necessary for the successful application of the null method.

The gimbal system 2 (fig. 32) is provided with frictional damping at the bearings. It is found that a short, heavy, damped pendulum of this type makes an excellent stabilizer.

A modification of this instrument has been constructed in which the rotation is produced electrically. A small 3-phase motor is mounted on the axis of the armature. The stray field of the motor, revolving at the same speed as the armature induces no e. m. f. in the latter; and the symmetrical position of the motor with respect to the armature prevents any twist of the earth's field.

GYROSCOPIC COMPASSES.

A magnetic compass surrounded by the unsatisfactory conditions found in service on aircraft is, at best, working under great disadvantages. Depending as it does upon the relatively weak horizontal component of the earth's magnetic field for its action, the instrument at the outset is not endowed with an actuating force of any appreciable power. Coupled with this disadvantage it has the disturbing influences presented by the uncertain and more or less variable magnetic fields developed by the power plant and auxiliaries of the system.

Among the interesting and promising substitutes for the magnetic compass is the gyroscopic compass. One of the obvious advantages of such an instrument is its independence of the earth's magnetic field as well as of the disturbing fields of the aircraft itself. On the other hand, the gyroscopic compass is necessarily larger and heavier than the magnetic compass, more complicated in design, and costlier to construct. In the various types of gyroscopic compasses in use on shipboard, the gyroscopic system is not neutrally balanced, use being made of a gravitational couple to keep the gyroscope precessing into the meridian. The system is consequently subject to disturbing forces whenever accelerations are present as on aircraft, and these disturbances persist for some time after the acceleration has ceased. Errors from such causes so far have proven a formidable difficulty in the development of gyroscopic compasses for aircraft.

A certain instrument, gyroscopic in principle, now under development in America consists of a neutral gyro in the form of a steel sphere resting upon an air film and rotated at an extremely high speed by a jet of air from a small compressor. The gyro element is surrounded by a suitable spherical housing, the lower half of which is mounted upon a frictional plane so as to be free to swivel about a vertical axis coincident with that of the inlet tube of the air jet. The plane is made frictional practically by the leakage of air from the inlet which forms a film. The lower half of the spherical bowl has a shallow channel cut in one side and extending toward the top. It is the air escaping from this channel which causes the sphere to rotate. It is intended that the sphere when once started spinning with its axis of rotation horizontal and pointing toward the north shall maintain that position indefinitely. The action of the channel above mentioned is such as to cause the lower hemisphere, which is free to swivel, to always turn into a position so that the plane of the channel is perpendicular to the axis of rotation of the sphere. Hence, if a compass card is mounted in a horizontal position on the lower hemisphere it will indicate the compass direction. The system above described is subject to certain inherent difficulties but presents an interesting attempt to solve the compass problem.

RECORDING COMPASS.

A foreign inventor has designed a recording compass which allows the flyer to follow the progress of the flight. A stylus is connected with the rotating system in such a manner as to record upon a suitable chart, rotated by a clock movement, the deviations from the true course both in magnitude and duration. This makes possible a subsequent proportionate correction.

DANISH AND SWISS COMPASSES.

Following are descriptions of the Knudsen compass and the Stoppani double pivot inverted compass.

KNUDSEN COMPASS.

The Knudsen compass (fig. 34) is a Danish instrument of the liquid-damped (alcohol mixture) type with a horizontal card. The card is marked with the 32 points subdivided into quarter points. It is attached to a small float chamber which also carries two magnets and

FIG. 34.—Knudsen compass.

FIG. 35.—Stoppani double pivot inverted compass.

a sapphire cup bearing on its lower surface. The pivot is supported on a spider near the bottom of the bowl. It consists of an alloy point set in a short brass rod.

The bowl is cylindrical, 106 millimeters in diameter and 60 millimeters in depth with diaphragm expansion base protected by a heavily weighted cap. A filler hole closed by a screw is set in the side of the bowl. The glass is held in place by a brass ring. Above this is a rotatable brass ring carrying a red and white index pointer for use in course setting. Another ring fixed to the first is graduated in single degrees from 0 to 360. This ring carries a small movable red index on its outer rim. The interior of the bowl is painted white and has two black wire lubber-lines set 90° apart.

The suspension consists of gimbals supported in a yoke. No provision is made for compensating magnets or for illumination.

This compass has a period of about 17 seconds. Its weight is 3.5 pounds.

STOPPANI DOUBLE PIVOT INVERTED COMPASS.

This compass (fig. 35) is a horizontal-card, liquid-filled (alcohol mixture), inverted type. It is designed to be mounted directly above the pilot in a position as remote as possible from disturbing magnetic influences. The observation glass is held in place by a ring graduated

at 10° intervals at the underside of the bowl (120 millimeters diameter, 100 millimeters depth), while a diaphragm expansion member covered by protective housing forms the upper end. The bowl is hung upon two hubs resting upon the gimbal ring of the mounting bracket. A vertical compensating rod extends above the mounting bracket and carries two adjustable sliding holders for the correcting magnets.

The bearing features of this instrument differ from those of the usual types. Instead of the single pivot arrangement common to the majority of aircraft compasses, this instrument is provided with two pivots (alloy), one mounted upon the inner surface of the cover-glass below the float and the other attached to the upper float surface. The float carries two cylindrical bar magnetic elements attached to the upper surface. The lower surface of the float is indented by a cavity holding a jewel cup while the upper jewel cup is held in a socket attached to a vertically adjustable post, mounted on a bridge member spanning the upper bowl surface and extending downward to meet the upper pivot. With the double pivot arrangement it is possible to make the buoyancy exactly neutralize the weight of the rotating system. This reduces the vibrational error which varies with the force exerted on the pivot by the vibration. The double pivots also prevent the balancing oscillations of the card with respect to the bowl.

The instrument described weighs 3.5 pounds.

TABULAR CLASSIFICATION OF COMPASSES.

Name.	Type.	Type of card.	Location of pivot.	Material of pivot.	Material of cup.	Magnetic element.	Damping fluid.	Mounting.	Compensated.	Period (complete).	Weight.	Page.
AMERICAN.										*Seconds.*	*Pounds.*	
General Electric air compass	Type B	Vertical	Card	Alloy	Sapphire	2 bars	Kerosene	Springs and felt	Yes	12	2.5	24
Navy Standard compass, No. 1	Mark XVI	Horizontal and vertical	do	do	do	do	Alcohol	Rubber (1)	Yes	20	3.7	25
(Sperry) Creagh-Osborne air compass	Mark II	Horizontal	do	do	do	do	do	Rubber and hair	Yes	18	3.3	26
Pentz compass		Vertical	do	do	do	do	Kerosene	Springs and felt	Yes	12	3.3	27
BRITISH.												
Creagh-Osborne air compass	Type 5/17	Vertical	Card	Agate	Sapphire	2 bars	Alcohol	Springs and felt	Yes	8-10	2.8	28
Creagh-Osborne aero compass	Type 259	do	do	do	do		do	do	Yes	25	2.1	29
Do.	Type 253	Horizontal	do	do	do		do	Springs and hair	No	25	7.0	29
R. A. F. pilot's compass	Mark II	Vertical	do	do	do		Zylol	Springs and felt	Yes	40-60	4.9	30
Air compass (quick period)	do	do	do	do	do	6 bars	Liquid	do	Yes		4.9	30
Campbell-Bennett aperiodic compass	Type 6/18, Mark II.	(1)	Magnetic system.	do	do	do	do	do	Yes	(1)	6.0	31
FRENCH.												
Aéronautique militaire compass		Horizontal	Bowl	Alloy	Sapphire	2 bars	Alcohol	Gimbals	No	17	3.3	32
Aéronautique militaire 1 compass		do	Card	Jewel	Jewel	do	do	Rubber (1)	Yes	16	6.0	33
Mauve compass		do	Bowl	Alloy	Sapphire	do	do	Springs	No	25	1.7	34
Do.		Horizontal and vertical	do	do	do	do	do	do	Yes	24	2.4	34
DeVries and Courbet compass		do	do	do	do		do	do	Yes	15	1.7	35
Monodep compass		Horizontal	Card	do	do	2 plates	Air	Gimbals	No		1.2	35
Favé air-damped compass		(1)	Magnetic system.	do	Jewel	12 bars	do	do	No	9	5.4	36
GERMAN.												
Kaiserliche marine kompass		Horizontal	Bowl	Alloy	Jewel	2 bars	Alcohol	Gimbals	Yes	25	6.4	37
Ludolph armee kompass	Type I	Horizontal and vertical	do	do	Sapphire	4 bars	do	Bracket	No		2.9	38
Sendtner armee kompass	Type III	Horizontal	Card	do	Jewel		do	Gimbals	Yes	25	4.8	38
Pfadfinder armee kompass	do	do	do	do	do	2 bars	do	do	Yes		5.5	39
Do.	Type IV	Horizontal and vertical	do	do	Sapphire		do	Bracket	Yes	25	3.2	39
Pfadfinder kompass für aviatik		Horizontal	Bowl	do	do	2 bars	do	Springs and gimbals	No	25	4.9	40
Remote indicating and remote control compass.		(1)	do	do	Jewel	4 bars	Liquid	Gimbals	No	25	27.1	41
MISCELLANEOUS COMPASSES.												
Bureau of Standard Earth Indicator compass (1)												44
Knudsen compass		Horizontal	Bowl	Alloy	Sapphire	2 bars	Alcohol	Gimbals	No	17	3.5	47
Stoppani double pivot inverted compass		do	Card and bowl	do	Jewel	do	do	do	Yes		3.6	47

[1] See text.

NOTE.—The author is pleased to acknowledge his indebtedness to Mr. K. H. Beij and Mr. C. L. Seward, of the Bureau of Standards, who assisted in the preparation and checking of parts of this paper.

REPORT No. 128.

DIRECTION INSTRUMENTS.

PART IV.

TURN INDICATORS.

By R. C. Sylvander and E. W. Rounds.

SUMMARY.

This part gives a brief history of the development of airplane turn indicators, with detailed descriptions of all known types and makes. The results of laboratory and flight tests are given for the several available gyroscopic turn indicators.

INTRODUCTION.

The turn indicator, which until recently had not come into general use, was early realized to be necessary for flying when no objects outside the plane were visible.

A properly functioning turn indicator shows to the pilot whether the airplane is flying on a straight course or is turning. It is not possible even when using the turn indicator to steer a perfectly straight course under all conditions, as this depends on the smoothness of the air, the manœuverability of the airplane, and the fact that before a turn is indicated it must have already started. However, the use of the turn indicator combined with the lateral inclinometer and air speed meter makes it possible for the pilot to keep the airplane in a safe flying attitude and to make good a desired course within fairly close limits.

The use of inclinometers and pendulums of various types for indicating lateral equilibrium of the airplane have been in use practically from the time when flying was first begun. When the airplane flies on a straight course, these devices serve to indicate turns about the longitudinal axis of the machine. They do not, however, indicate a turn of the airplane from its course.

As early as 1899 a gyroscopic device for indicating angular motion was patented in England by Van Overclift. The fundamental idea of the instrument is that of the modern airplane turn indicator.

It is probable that the first turn indicator intended for aircraft was explained in principle in a memorandum by C. C. Mason and Sir Horace Darwin to the British Advisory Committee for Aeronautics in 1912. Some experiments were made at that time, but it was not until March, 1918, that patent was applied for on the static head turn indicator developed from the above principle. This instrument is now being manufactured by the British Wright Co. and is described below.

In January, 1917, two Frenchmen, J. de Lesseps and R. Courtois-Suffit, patented a differential pressure instrument, using Pitot, Venturi, or other tubes placed one on each wing and as far as possible from the plane of symmetry. This device was intended to show also the air speed of the airplane.

In May, 1917, J. B. Henderson applied for a patent on what seems to have been the first gyroscopic turn indicator. In this instrument precession of the gyro was communicated through bevel gears to a pointer moving over a scale.

At about the same time, Smith and Lindeman developed, in England, the gyroscopic instrument described below as the Royal Aircraft Establishment turn indicator.

During the war the Germans developed and used an electrically driven gyroscopic turn indicator invented by Drexler. A detailed description of this instrument is given in a later paragraph.

Two gyroscopic turn indicators, the Sperry and the Pioneer, are at present being manufactured in this country and are described below.

Apparently the latest British turn indicator is one devised by G. H. Reid. This instrument, according to available information, is of the air-driven gyroscopic type. A turn is shown to the pilot by the lighting up of electric lamps, which obtain their current through a commutating device actuated by precession of the gyro. A mercurial inclinometer is combined with the turn indicator and a series of lamps is lighted by the passage of current between contacts through the mercury in the inclinometer tube.

It is probable that other turn indicators have been constructed, since various methods have been suggested, such as the use of the apparent increase of weight on a turn and the measurement of the difference of electrostatic potential of the wing tips.

In general there are two types of turn indicators in use, the gyroscopic and the differential pressure types.

The gyroscopic turn indicator depends in principle upon the action of a gyroscope which is mounted in such a way that it may precess about only one axis. The turning movement of the plane causes precession about this axis and this precession is indicated on a dial by means of a suitable mechanism.

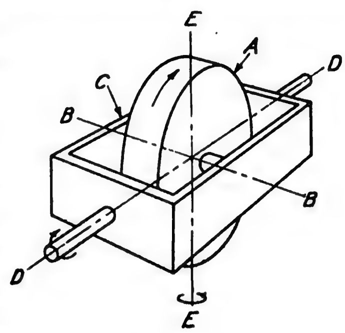

FIGURE 1.

The principle is probably best illustrated by reference to figure 1.

The gyro wheel (A) is mounted on an axis (B–B) which should be athwartships and normally horizontal. The bearings for (B–B) are in a frame (C) which is in turn mounted on the axis (D–D) on bearings in the main case of the instrument. The axis (D–D) should be in the same plane as (B–B) and should be mounted in the aircraft in a fore-and-aft position. The whole unit should be balanced about (D–D); the gyro should be carefully balanced about its axis of rotation (B–B). If mounted as described above the effects of pitching, rolling and accelerations are made negligible.

With the gyro wheel running in the direction shown by the arrow, suppose the plane carrying the instrument to make a turn to the left, as indicated by the arrow about the vertical axis (E–E). The turn will cause precession of the gyro unit about (D–D) as indicated. A turn to the right will cause precession in the opposite direction. The amount of this precession is controlled by a spring system and is usually limited by the frame striking a positive stop. Sufficient motion and power is thus obtained for actuation of the indicating mechanism.

The gyro may be driven by varied means. In one type of turn indicator it is in the form of a windmill and is driven by the air stream directly. In another type it is actuated by air which is drawn past the rotor by the suction of a Venturi tube which is mounted in the air stream, the gyro being mounted where convenient. In still another type the gyro is the rotor of a small induction motor which is driven by a fan generator mounted in the air stream.

The differential pressure turn indicator depends in principle upon the effect of centrifugal force developed on a turn and the difference in static pressure due to change in altitude of two static tubes mounted symmetrically on the extreme ends of the wings, and pivoted in such a way as to head directly into the air stream at all times. The pressures are communicated through tubing to either side of an extremely sensitive differential pressure gage.

The action is probably best explained by the following extract from a paper by Sir Horace Darwin entitled "The Static Head Turn Indicator for Aeroplanes."

"In order to make the action clear, we will assume that the aeroplane is moving in a circle, that it is not banked, and that the air tube connecting the static heads is horizontal and points along a radius of the circle. The forces acting on the air in this tube are:

"1. Gravity acting vertically downwards. As the tube is horizontal this will cause no difference of pressure at the manometer nor cause any tendency of the air to move along the tube.

"2. The atmospheric pressure at the static heads. As the tube is horizontal the pressures at the ends of the tube are equal and in opposite directions, and no effect is produced on the manometer.

"3. The pressure of the inner surface of the tube against the air; this clearly has no effect on the manometer.

"4. Centrifugal force is the one remaining force which can cause a movement of the differential manometer. The air will tend to move along the tube in an outward direction and can only be prevented from so doing by a difference of pressure on the two sides of the diaphragm in the manometer. It is this difference of pressure which is indicated on the manometer and shows a right or left hand turn.

"All turns, however, are banked and this assumption is only made to make the action clear.

"Let us now consider a banked turn and assume that the aeroplane is banked at the correct angle. By the correct angle is meant an angle which causes no side slip; that is, such an angle that the apparent direction of gravity (that is, the resultant of gravity and centrifugal force) is at right angles to the plane of the wings.

"Again consider the forces acting on the air in the tube.

"1. As the banking is at the correct angle, the resultant of gravity and centrifugal force acts at right angles to the direction of the tube and has no effect.

"2. The pressure against the inside of the tube clearly has no effect.

"3. The atmospheric pressure at the two static heads is not equal; as the aeroplane is banked, the outer end is higher up and at a place where the air is at a less pressure. The differential manometer will show this difference of pressure."

An instrument of this type is described in detail below.

AMERICAN TURN INDICATORS.

THE PIONEER TURN INDICATOR.

The Pioneer turn indicator is shown in figures 2 and 3. This instrument depends in principle upon the action, described above, of a small gyroscope which is mounted in such a way as to allow precession only about an axis parallel to the longitudinal axis of the airplane.

The gyroscope is driven by a jet of air drawn into the case through a nozzle by the suction produced in the throat of a double Venturi tube, figure 8, mounted in the air stream.

As with all turn indicators of the gyroscopic type, care must be taken to mount the instrument so that effects of pitching and rolling are negligible.

Turning of the airplane about its vertical axis is indicated by the appearance of a white sector in the triangular-shaped openings of the dial. A turn to the right brings this sector into view in the right-hand openings and similarly, a turn to the left is shown in the left-hand opening.

The indicator weighs, with the Venturi tube, about 2½ pounds.

DESCRIPTION.

Figure 3 shows the mechanism. The gyroscope (A) is mounted in the aluminum frame (B) which is inclosed in the case (C) of the same material. The brass rotor is mounted on two short steel shafts (D) held in brass bushings (E). The shafts are hardened and form the inside races of specially designed ball bearings. The outer race is contained in a recess of the rotor and consists of a steel disk taking the side thrust and a steel ring in which five three-sixteenths-inch steel balls run. A brass disk pressed into the rotor holds the outer race in place, protects

the bearings from dirt, and serves to prevent loss of oil. A felt coil is held between the two bearings and acts as an oil retainer. Four holes in the thrust disk allow the lubricating oil to pass into the bearing.

The bearings are adjusted by screwing the bushings (E) in or out in the frame (B). The clamp screws (G) hold the bushings in place after adjustment.

Oil may be added to the central reservoir through one of the steel shafts (D) and its bushing, which are drilled axially. The removal of a plug (H) in the side of the case permits access to the oil hole.

FIG. 2.—Pioneer turn indicator.

The frame (B) is supported at each end on sets of special ball bearings at (J) and (K). Each bearing consists of a steel disk and a flanged ring which serve as thrust members, the latter also serving as the inner ball race, and a steel ring which forms the outer race. Twelve one-eighth-inch steel balls complete the bearing unit. All bearing surfaces are hardened.

Both bearings are held in position by brass plates, the one at (J) being screwed to the frame (B), while the other at (K) is fastened to the cast aluminum frame (L) which is secured to the forward end of the case (C).

The inner race of the bearing (J) fits over a brass pin or pivot (M) in the rear of the case (C). This pivot is drilled to connect with the intake port in the case and acts as the nozzle directing the jet of air downward onto the buckets (N) cut in the periphery of the rotor.

Precession of the gyroscope about the axis through bearings (J) and (K) is transmitted to the indicating disk (O) by a brass shaft on the end of which the disk screws. A second brass disk (P) is secured to one end of the frame (B). The gyro unit is balanced about the precession

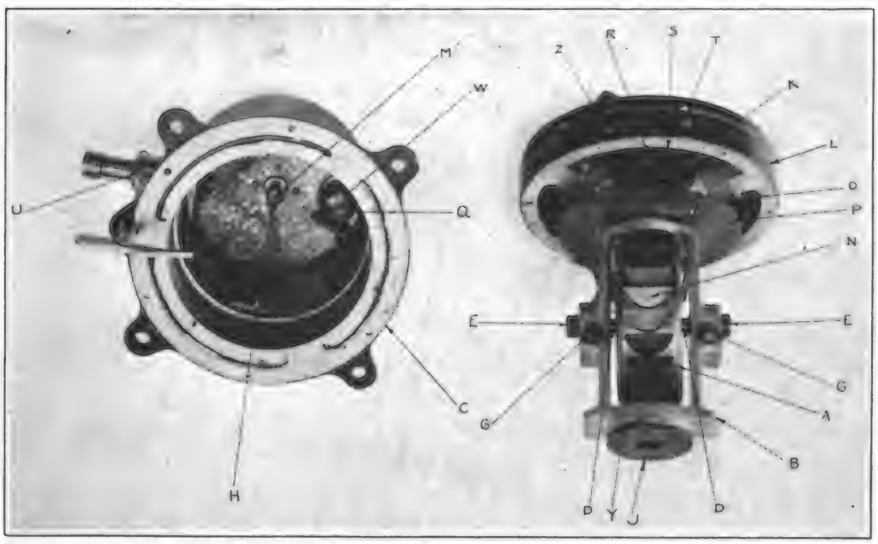

FIG. 3.—Pioneer turn indicator.

axis by means of solder placed on this disk. In an earlier type, instead of the disk (P), a circular reservoir partly filled with liquid was used as a damping device.

A rubber-covered stud (Q) screwed into the case (C) limits the angle of precession.

The gyro unit and indicator are normally centered by a bronze spring (R) which is fixed to the gyro unit at one end, eccentric to the axis of precession, by means of a swivel and at the other by a flat bronze spring (S) attached to the ring (L). A screw (T) changes the position of the strip (S) thus changing the tension of the spring (R) and the sensitivity of the indicator.

The main adjustment of sensitivity is provided by varying the opening of the exhaust valve (U). For convenience, seven positions are indicated on the dial. With the valve wide open maximum air flow and hence maximum speed of the rotor is obtained. Since the precessional force depends on the speed of the rotor, this setting gives maximum sensitivity.

The case is made air-tight by the use of shellac, so that all air flow is through the nozzle. The air intake is covered by a screen held by a cap which may also clamp in place a flexible metal tube for drawing dry air from any desired location in the airplane.

Lubrication of the rotor is described above. The precession bearing (J) may be oiled through a small copper tube (W) after the removal of a screw. The oil from the tube drops into a recess (Y) and flows into the bearing. Removal of the screw (Z) permits oiling of the other bearing (K).

TEST DATA.

Venturi suctions.—The suctions obtained from wind tunnel tests on the Pioneer Venturi tube with the indicator connected and its valve adjusted for maximum air flow are given below. All values are reduced to standard density (15.6° C. temperature and 760 millimeters mercury pressure).

Air speed in miles per hour.	Suction in inches of water.
40	8.4
50	13.2
60	19.5
70	27.1
80	35.9
90	45.0
100	54.9

Indicator calibration.—The calibration of a Pioneer turn indicator with an impressed suction of 19.5 inches of water, which corresponds to that obtained at 60 miles per hour air speed, is given below. The exhaust valve was wide open during the tests.

Per cent of full scale deflection.	Complete turns (360°) per minute.
2	0.05
25	0.16
50	0.38
75	0.68
100	1.15

Calculations show that, the air speed being 60 miles per hour, turns having a radius greater than 3.4 miles will not be shown.

SPERRY TURN INDICATOR.

The Sperry Mark I, Model A, turn indicator is shown in figures 4 and 5. The instrument is of the gyroscopic type which is described in principle above.

The gyro of the Sperry instrument is driven by a jet of air impinging upon cups or teeth cut in its periphery. The air enters through a hole in the top of the case and passes by the gyro rotor and out of the case through a tube directly below. This tube is connected to the throat of a double Venturi, shown in figure 7, which is mounted preferably in the slip stream of the propeller. The suction of the Venturi partially evacuates the case which is air-tight, air rushes through the jet, impinges upon the gyro, rotates it and passes out through the tube to the Venturi. The flow of air is sufficient to drive the gyro at a high rate of speed.

The mechanism of the turn indicator is arranged in such a way that when a turn to the right is made a white sector moves into view at the left of the dial. This indicates that the pilot should apply left rudder to bring the plane back to a straight course.

Means are provided for preventing excessive speed of the gyro. At a certain value of the suction a ball valve in the case opens and allows air to enter, reducing the vacuum and lessening the flow of air through the jet.

The instrument is designed to fit into a hole in the airplane instrument board, being held in place by four screws. The weight of the indicator and the Venturi combined is about 2¼ pounds.

DESCRIPTION.

As shown in figures 4 and 5 the turn indicator mechanism consists of a brass rotor or gyro (A) mounted in a cast aluminum frame (B). The frame carries a disk (C) on the upper part of which is painted a white sector. The movement of this sector past either of two diametrically opposite openings in the dial shows the direction and roughly the magnitude of the turn. When the white does not show the airplane is supposed to be on a straight course. The instrument does not indicate directly the direction of turn but the direction in which the pilot should steer to correct for the turn; i. e., a turn to the right causes a left deflection which is made zero by moving the rudder to the left.

The gyro is carried on radial ball bearings which are lubricated by oil-soaked cotton waste packed in the aluminum housings (D), holding the special gyro shaft ball bearings. The gyro rotor is built up of three parts riveted together. The gyro shaft, which is in one piece, is of

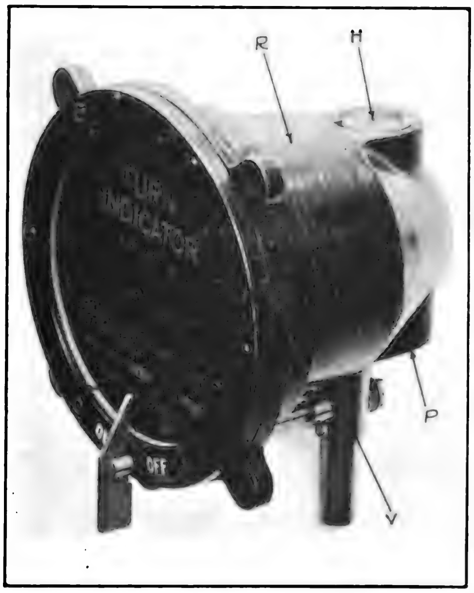

FIG. 4.—Sperry turn indicator.

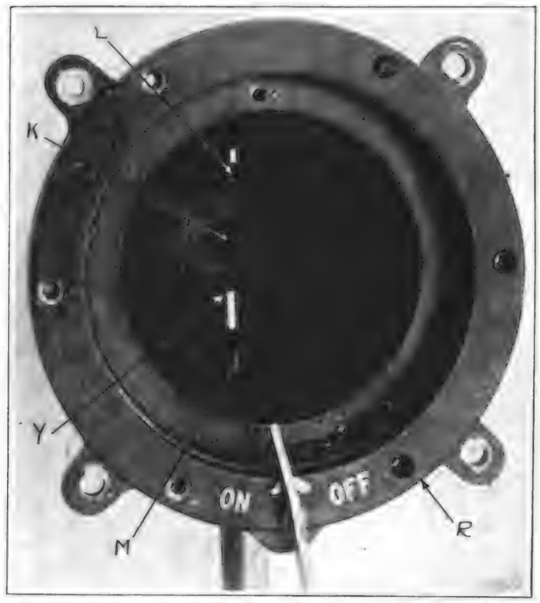

FIG. 5.—Sperry mechanism.

steel with bearings one-eighth inch diameter. The side play of the gyro is adjusted by means of screws (E) with lock nuts (F), one on each side, the ends of which bear against the ends of the gyro shaft. The aluminum caps (G) are threaded for these adjusting screws and also serve to retain the oil and keep out dirt and moisture.

The gyro has buckets cut in its periphery and is driven by the impact of a jet of air which enters through the screened hole (H) and the nozzle (L) and passes out of the case through the hole (M) and the valve (V) to the throat of the Venturi tube, figure 7. Adjustment of the valve (V) regulates the flow of air and consequently the sensitiveness of the instrument. The valve may be closed and the instrument shut off if desired.

The gyro frame is carried fore-and-aft on steel pivot and cup precession bearings, the pivot (K) being fixed to the back of the case (R) and the pivot (N) to an aluminum bridge (O) which is placed across the front of the case opening. (N) is adjustable and is locked in place by a check nut. The gyro mechanism can easily be removed from the case as a unit, as shown in figure 6.

The gyro is normally held in position by the spring (S), which is so mounted that its tension increases as precession takes place. Too great a motion is prevented by the rubber-covered arms (T) striking the bridge (O).

The sensitivity is not adjustable except by installing a spring of different characteristics.

Protection against suction which would cause excessive gyro speed is provided by a ball valve at (P), figure 5, which automatically allows air to enter the case through the hole (Y) when its evacuation reaches a certain predetermined value, thereby maintaining a steady flow of air and preventing racing of the gyro. The steel ball is held against its seat by a small helical compression spring. As soon as the difference between atmospheric pressure and that inside the case exceeds the strength of the spring the ball moves upward, air rushes in and the difference in pressure tends to reduce to its former value.

TEST DATA.

Venturi suctions.—The suctions obtained from the wind tunnel tests on the Sperry Venturi tube with the indicator connected and running at full flow, are given below. All values are reduced to standard density (15.6° C. temperature and 760 millimeters mercury pressure).

Air speed in miles per hour.	Suction in inches of water.
40	6.0
50	9.7
60	13.8
70	18.0
80	22.4
90	27.6
100	32.8
110	38.5

Indicator calibration.—The calibration of a Sperry turn indicator with an impressed suction of 13.8 inches of water, which corresponds to that obtained from the Venturi at 60 miles per hour air speed, is given below. The exhaust valve was wide open during the tests.

Per cent of full scale deflection.	Complete turns (360°) per minute.
2	0.06
5	0.31
50	0.86
75	2.72
100	4.65

Calculations show that, the air speed being 60 miles per hour, turns greater than 2.5 miles radius would not be indicated.

PIONEER TURN AND PITCHING INDICATOR SYSTEM.

The Pioneer turn and pitching indicator system consists of a turn indicator, a pitching indicator and a power unit for driving the indicators. It is intended for use on dirigibles and is designed to function at air speeds much lower than is possible with the Venturi-driven type of turn indicator.

The turn indicator, shown in the left of figure 9, is the same as the Pioneer turn indicator described in detail above.

The pitching indicator, shown in the right of figure 9 is very similar to the turn indicator except that the sensitive element is so mounted in the case as to indicate departures from a horizontal plane instead of departures from a vertical plane. A downward deviation of the course causes the luminous part of the disk to show in the lower opening of the dial and vice versa. The instrument is provided with similar adjustments and means for oiling as are found in the turn indicator.

Two power plants or suction pumps are shown. The earlier type, figure 10, consists of a laminated wooden propeller (A) mounted in ball bearings. Channels (H) extend from the tips of the blade to the propeller axle which is hollow and connects through a port hole with the hollow tube (C). The tubes (C), (B), and (D) are arranged so as to form a rigid mounting for the propeller; (C) has two connections for flexible tubing, which lead to the indicators. The

air in the channels (H) is thrown outward by centrifugal force as the fan rotates, drawing more air in through the tube (C) and the indicators.

The propeller pump is 24 inches in diameter and weighs approximately $4\frac{1}{2}$ pounds.

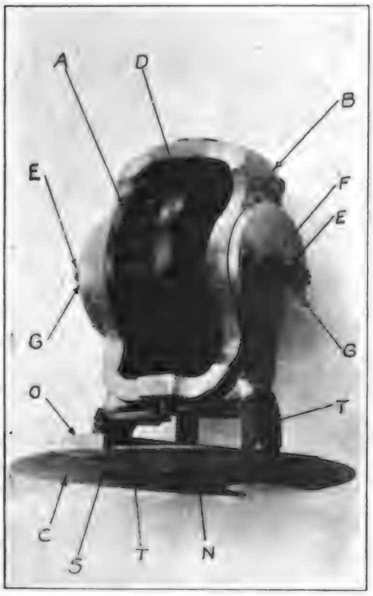

Fig. 6.—Sperry mechanism.

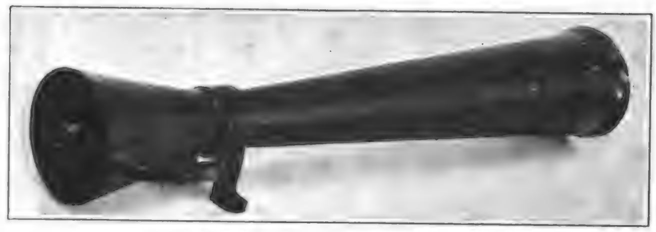

Fig. 7.—Venturi tube for Sperry turn indicator.

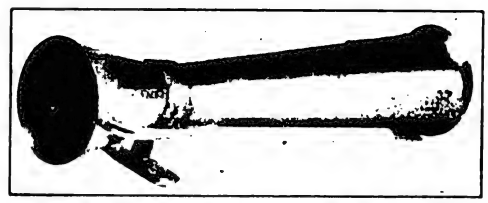

Fig. 8.—Venturi tube for pioneer turn indicator.

The later type, figure 11, consists of an electric pump. A 12-volt direct current series-wound motor in an aluminum case (A) drives a brass four-bladed paddle (B) fixed to its shaft. The paddle (B) forces air out of the case through the groove (C). The flow of air is as follows: through the indicators, flexible tubing to the connections (E) which are fixed to the brass cap (D), and past the motor through the four holes (F) into the paddle case, where it is forced out

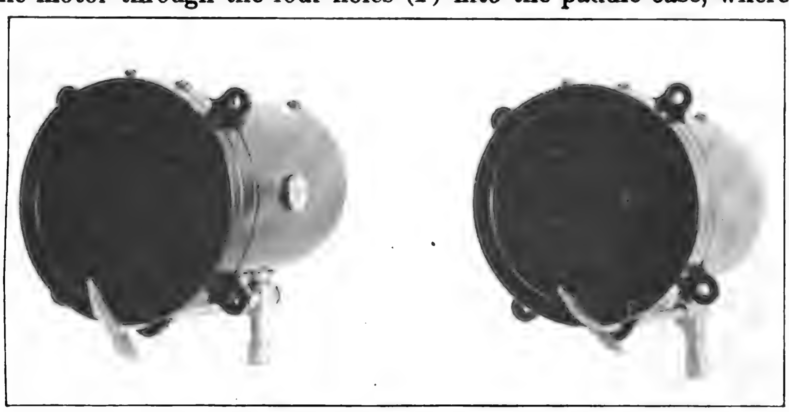

Fig. 9.—Pioneer turn and pitching indicators.

by centrifugal force as described above. The aluminum cover (G) forms the case of the instrument.

The pump stands about $5\frac{3}{4}$ inches high and the diameter of its base is 7 inches. The outfit weighs about $4\frac{1}{2}$ pounds.

TEST DATA.

Propeller pump.—Preliminary wind tunnel tests showed that the design of the propeller is such that it would rotate at speeds considered unsafe even when the air speed is as low as 25 or 30 miles per hour. The results given below, therefore, are for low air speeds only.

The suctions in inches of water and rotational speeds in revolutions per minute are tabulated below for various air speeds. The air speeds are reduced to standard conditions. During

the tests a turn indicator and a pitching indicator were connected with their valves adjusted for maximum air flow.

Air speed, miles per hour.	Propeller speed, revolutions per minute.	Suction, inches of water.
7.3	610	0.90
9.7	940	2.23
10.9	1,220	3.55
12.5	1,380	4.87
14.4	1,580	6.75
17.0	1,940	9.80
19.6	2,250	13.10
22.7	2,600	17.80

The suction obtained at an air speed of 19.2 miles per hour was sufficient to operate the indicators in a satisfactory manner.

The data indicates that at 60 miles per hour air speed the revolutions per minute of the propeller would be about 7,500.

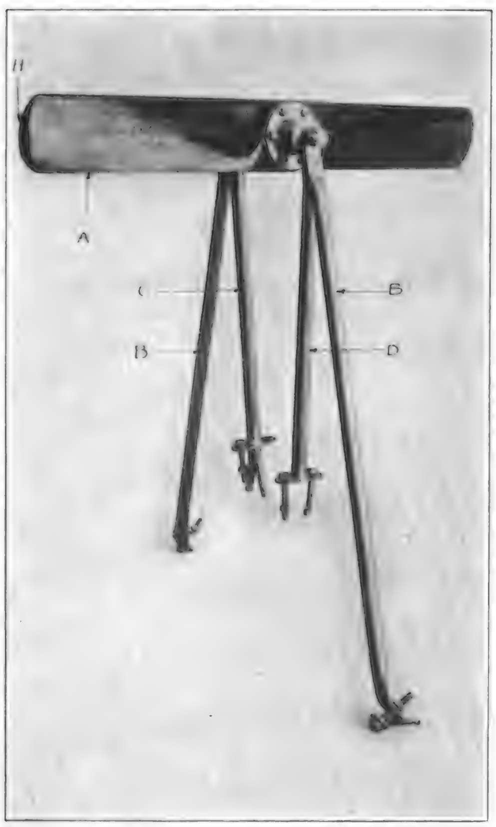

FIG. 10.—Pioneer propeller pump.

FIG. 11.—Pioneer electric pump.

In a destructive whirling test the propeller broke at a speed of 5,800 revolutions per minute.

Electric pump.—The suctions in inches of water at 26° C. for various voltages are tabulated below, together with the amount of current required. Both turn and pitching indicators were connected and running with their valves adjusted for maximum flow of air.

Volts.	Amperes.	Suction, inches of water.
6.2	6.4	5.9
7.5	6.2	7.1
8.8	6.3	8.3
11.8	6.3	10.6

For best performance of the system the impressed voltage should be about 12 volts.

BUREAU OF CONSTRUCTION AND REPAIR STATIC HEAD.

Figure 12 shows an experimental head developed by the Bureau of Construction and Repair, United States Navy, for use with a differential type turn indicator. Three types of head were made, a Pitot tube, a static tube, and a closed tube. At about the same time the British Wright turn indicator which is based on similar principles was produced in England and consequently the work was abandoned.

BRITISH TURN INDICATORS.

R. A. E. TURN INDICATOR.

The R. A. E. Mark V turn indicator, manufactured by the Royal Aircraft Establishment, is shown in figures 13 and 14.

This instrument is a single unit type, deriving its motive power from the air stream acting directly on the inclined sides of holes in the gyroscope. This necessitates its being mounted close to the side of an airplane, a disadvantage in some types.

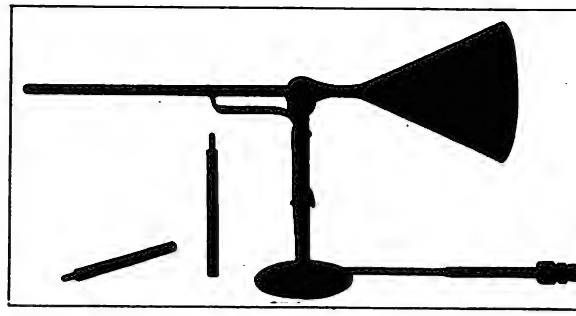

FIG. 12.—Bureau of C. & R. static head for experimental differential pressure type turn indicator.

The overall length of the turn indicator is slightly over 14 inches and its weight is 3½ pounds. A bracket for mounting is clamped around the frame and its weight adds perhaps another half pound to the complete installation.

In mounting the indicator care must be taken to mount it with the tubular portion of the case parallel to the transverse axis of the airplane. If this is not done pitching of the airplane will be shown as a turn on the indicator although with the indicator horizontal and set nearly athwartships the effect of pitching will be small. There is usually no reason for not setting the instrument properly and in service no trouble should be experienced from this source.

Looking forward the gyroscope rotates counter-clockwise, a turn to the right causing precession which turns the pointer to the right of the zero position. A turn to the left similarly moves the pointer to the left of the zero.

A lever, the knob of which appears at the left of the dial, is capable of being set in any one of 11 different positions, giving 11 different degrees of sensitivity. In the notch labeled zero the sensitivity is a maximum, while in notch No. 10 it is a minimum. The zero point is adjustable by turning the bezel ring.

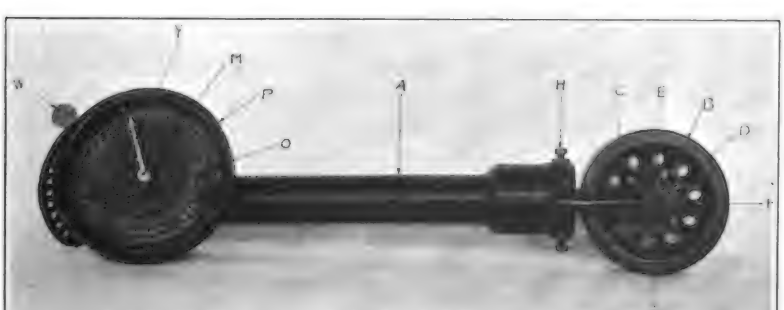

FIG. 13.—R. A. E. turn indicator. Mark V.

DESCRIPTION.

As shown in figures 13 and 14 the instrument consists of a main frame of cast aluminum in which most of the mechanism is housed.

The gyroscope (B) is mounted on two sets of double annular self-aligning ball bearings. These are in turn mounted on a small steel shaft (Z) which is supported in the yoke (C) by two threaded bronze bushings (D). Set screws (E) hold the bushings after being adjusted to the proper position. A brass disk or washer (F) is placed next to the bearings on each side to protect them from the weather.

Two rows of 10 holes each are drilled in the web of the rotor at an angle of 45° with the plane of rotation. It is the action of the air stream on the sides of these holes which produces motion.

The yoke (C), which is of bronze, is held in position on a steel shaft (G) which runs to the head of the instrument, by two set screws (H). The yoke is adjustable about the axis of the shaft.

This steel shaft is mounted at each end in double annular self-aligning ball bearings. The bearing at the yoke end is held in a bronze sleeve fitted into the aluminum case. The bearing is held in place by the position of the yoke. The head end of the shaft is mounted in a similar ball bearing of smaller dimensions, held in position by a bronze plate screwed to the aluminum housing.

A stud (J) is screwed to the plate and is used to limit the angle of precession, as noted below.

On the end of the shaft is screwed a brass flanged disk (K) which positions the shaft in the bearings. This disk gear is held in place by a washer cut to fit the shaft which is flattened on two sides. The washer is pinned to the disk and a brass nut (L) holds it in place.

A hole in the disk fits over the stud mentioned above. The angle of precession is limited to approximately 40° by the sides of the hole striking on the stud (J). The flanged disk (K) has teeth cut in about a quarter of its flange, forming a crown sector, which meshes with a 10-tooth pinion on a shaft (M) carrying the pointer (Y).

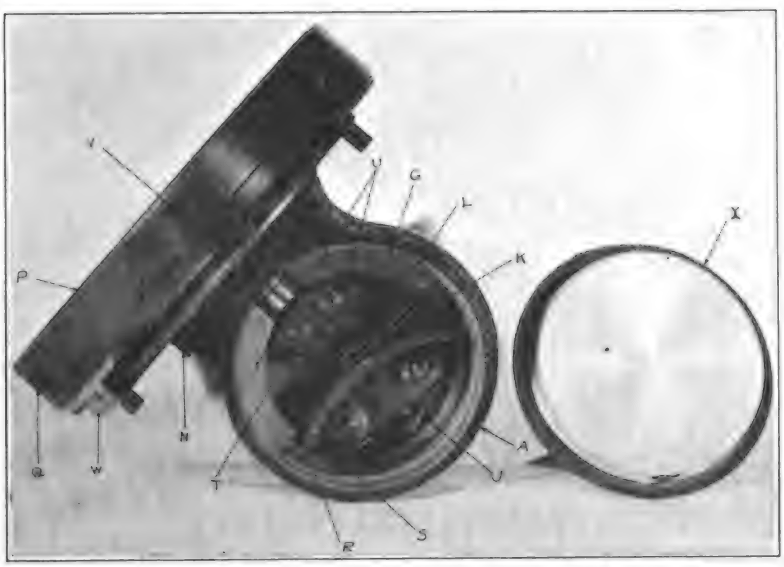

FIG. 14.—R. A. E. turn indicator. Mark V.

The shaft (M), and with it the pointer, rotates in a bronze bushing held in place by a set screw (N). A light wire spring bearing against the shaft tends to prevent chattering. The dial (O) is connected to the bezel ring (P) by a small screw (Q) so that turning the bezel changes the position of the zero.

A flat steel spring (R), shown inside the head of the instrument, acts as a centralizing device and is also used to adjust the sensitivity. The spring bears against a brass sector (S) bolted to the crown gear. The flange of this sector is the arc of a circle whose circumference passes through the axis of precessional rotation. As precession takes place, the line of contact moves off center and a couple is set up tending to retard further precession and return the parts to zero position.

To balance the weight of the flange bearing against the spring, about the center of rotation, a brass counterweight (T) is mounted with its center of gravity diametrically opposite that of the flange. This device neutralizes the effect of acceleration along the longitudinal and vertical axes of the airplane.

The spring is supported at each end by a brass sector (U) sliding circumferentially in a groove in the aluminum case. A symmetrical cam (V) moved by the lever (W) shown at the left of the dial spreads the sectors so that the ends of the spring subtend a greater arc, thus increasing the pressure of the spring against the flange. This action decreases the sensitivity by supplying a greater couple to retard precession.

A light aluminum cover (X) protects the mechanism from the weather.

The mechanism of the instrument is such that when a right turn is made the pointer (Y) moves to the right and vice versa. During the first tests it was found that the position of the pointer changed when the sensitivity was changed. Upon examination the spring which is

used to center the pointer was found to have received a permanent set. This was remedied after which the position of the pointer was unchanged by varying the sensitivity.

All bearing surfaces are either bronze or SKF ball bearings. No particular means for lubrication is supplied but all ball bearings are packed with light grease or vaseline and other bearings oiled.

THE BRITISH WRIGHT TURN INDICATOR.

This aero turn indicator originally known as the Darwin turn indicator, consists of two static heads mounted symmetrically, one on each wing tip, in such a way that they always tend to head into the direction of the relative wind, together with an Ogilvie differential pressure gage mounted in the pilot's cockpit and connected to the static heads by tubing.

An adjustable scale is provided which should be set to the zero mark during straight flight as soon as possible after leaving the ground, as slight changes in the position of the pointer are likely, due to the variation in construction of the static heads and the likelihood that the pressures at the two static heads will not be equal. The variation in the zero position with a properly functioning gage is probably less than 10°.

The action of the static head turn indicator depends on the effect of centrifugal force developed on a turn and the difference in pressure due to change in altitude of the static heads,

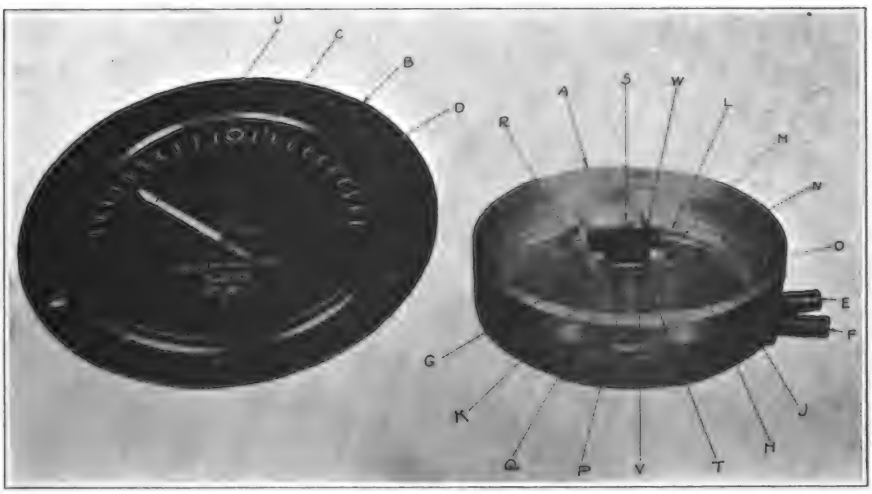

FIG. 15.—British—Wright turn indicator.

as described above. The pressures are transmitted to the gage in such a way that a turn to the right causes the pointer to move to the right of the zero.

The pressure gage is approximately $5\frac{5}{8}$ inches in diameter and weighs about 12 ounces while the two static heads with their supports have an overall length of nearly 3 feet and weigh about 3 pounds. To these weights must be added that of the tubing connecting the gage with the static heads.

DESCRIPTION.

The differential pressure gage shown in figure 15 is very similar in construction to the gage used with the Ogilvie air speed indicator. The case consists of a cast aluminum back (A), to which is threaded an aluminum flange (B), in which is held the adjustable scale (C), and the aluminum dial (D) protected by a glass face. A small set screw prevents the flange from unscrewing due to vibration. A rubber gasket between the face, a brass ring and the back (A) makes the case air-tight. Two brass nipples (E) and (F), screwed into the case provide connections for the lines from the static heads.

The sensitive element consists of an india rubber diaphragm (G), held securely against a shoulder in the case by a rubber gasket (H) and aluminum diaphragm ring (J). The ring (J) is in turn held by the cast aluminum frame (K) which is separated from the ring by a rubber

gasket (L) and a paper gasket (M). The frame is held firmly in place by an aluminum ring (N) which screws into the case (A). Two holes (O) are sockets for a special wrench used in turning the ring.

The pressure of the ring (N) is transmitted to the edges of the rubber diaphragm (G) and makes it air-tight. The case in front of the diaphragm is made air-tight by the tightening of the flange (B) against the rubber gasket mentioned above.

Thus the case is divided into two air-tight chambers separated by the rubber diaphragm (G). The nipple (E) leads into the chamber behind the diaphragm and is connected to the static head mounted on the starboard wing tip. (F) leads through a hole in the rim of frame (K) into the chamber forward of the diaphragms and is connected to the port static head.

Cemented to the diaphragm near its center is a small aluminum disk (P) with a small steel hook attached to it. Over this hook is looped one end of a silk thread which runs over a guide roller (Q) supported in two brass bushings (R) screwed into the aluminum cross members of

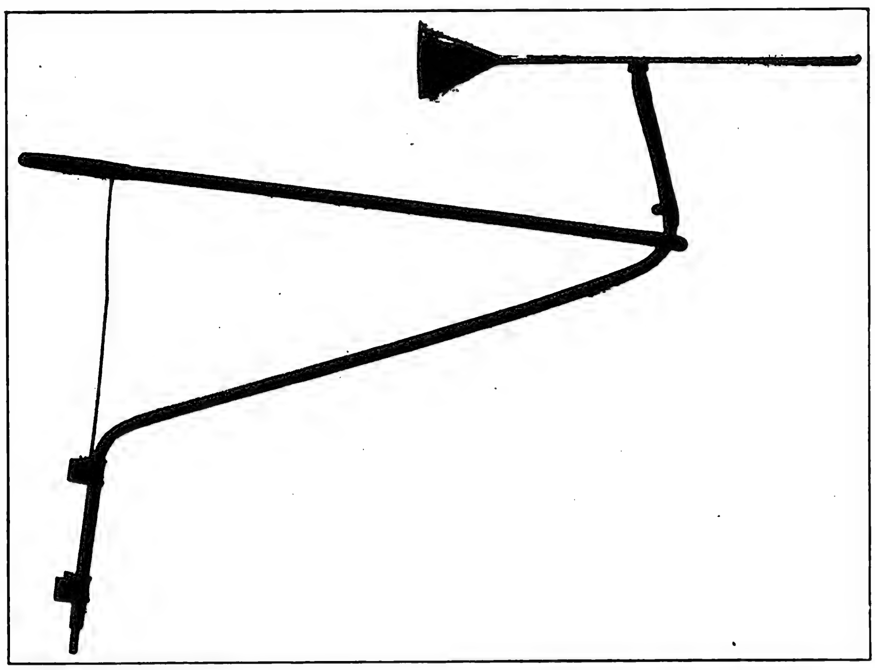

FIG. 16.—British—Wright static head.

the frame (K). The other end of the thread is knotted through a hole in the pointer spindle (S). A small hairspring (T) resists rotation of the spindle with enough force to keep the thread taut.

Motion of the rubber diaphragm is communicated to the pointer (U) by means of the silk thread. When the diaphragm moves forward the slack in the thread is taken up by the tension of the hairspring.

The pointer spindle (S) is carried in two bearings which consist of a brass bushing screwed into the aluminum cross member (V) which is part of frame (K), and the brass plate (W) screwed to the frame (K).

No lubrication of the instrument is necessary as the bearings have plenty of clearance, the hairspring taking care of any possible back lash. Oil would, of course, tend to spoil the rubber diaphragm.

Two static heads such as are shown in figure 16 are mounted, one on each side of the airplane axis, on an A-shaped bracket which fits on the outboard forward strut of the airplane, The head itself consists of a three-eighths inch brass tube closed at the forward end with a stream line plug.

Twenty-four holes of one-thirty-second inch diameter are grouped in four rows around the circumference of the tube. The rows are one-quarter inch apart and start 3 inches from the end of the tube, the air flow here being parallel to the sides of the tube.

The rear of the tube is also plugged and a copper cone with its base aft furnishes directional stability, so that the tube tends to always head into the direction of the relative wind.

The head is hinged at its center of gravity to a square bronze shaft which pivots in the end of a bronze spindle attached to the bracket supporting the head, allowing through certain limits a universal joint action.

Around the square shaft and attached to the head is secured a copper flange on which a flexible rubber tube is made fast extending down and around the supporting spindle to a copper tube which transmits the static pressure to the gage on the instrument board. The rubber tube serves two purposes, providing a flexible connection holding the pivot in its place and carrying the pressure to the gage.

The brackets holding the static heads are of triangular form, the copper transmission tube forming the lower side, a steel tube the upper, and a brass strip parallel to the strut making up the base. Metal straps and saddles hold the brackets in place on the struts.

GERMAN TURN INDICATOR.

DREXLER AIRCRAFT STEERING GAGE.

The Drexler aircraft steering gage is shown in figures 17 and 18. It consists essentially of an electrically driven gyroscope connected with the pointer in such a way that when a turn is made to the right the precession of the gyro moves the pointer to the right of its zero position. Similarly, when a turn is made to the left, the pointer moves to the left.

FIG. 17.—Drexler steering gauge-assembly.

An inclinometer, consisting of a glass tube which contains a steel ball whose motion is damped by a liquid, is mounted on the face of the instrument above the scale. The inclinometer is interconnected with the gyroscope in such a way that precession of the gyro may also tilt it.

As in the usual types of inclinometers, the ball is in the center of the tube when the plane is in lateral equilibrium.

It is the claim of the manufacturer that "many flying machines, according to their construction, should in turns not be inclined at the actual angle corresponding to the theoretical deflection of a liquid or solid pendulum, which, when flying in curves, will adjust itself according to the resultant of the centrifugal force and gravity."

Since, for all practical purposes, the proper angle of bank depends only on the speed and radius of the turn, and not on the weight or type of airplane, the interconnection of the gyro and inclinometer is a needless complication.

Further information seems to indicate that the tilting of the inclinometer with precession of the gyro was intended to be used in training students. Thus, if a student tended always to underbank his machine, the inclinometer would be set to indicate a less bank then actually was being made, influencing the flyer to bank his plane still more. This could readily lead to dangerous positions, and its practice should not be tolerated.

No need or good reason for interconnecting the gyroscope and inclinometer can be seen. However, mounting the inclinometer close to the turn indicator is of great advantage.

The gyroscope is a three-phase induction motor with short-circuited rotor, the current being supplied from a streamlined generator driven by a windmill in the air stream.

The sensitivity is not adjustable, but the motion of the pointer is damped hydraulically, as described below.

A light is mounted inside the case and derives its current from the motor circuit.

The indicator itself stands with its bracket about 8½ inches high and is of about the same width. Its weight is 8½ pounds. The generator weighs 5¼ pounds, making the total installation weight with windmill and connecting cable about 15¾ pounds.

Springs are provided in the bracket to absorb vibration.

Modifications of this turn indicator are made combining in one unit an altimeter, an air speed meter, an inclinometer, and the turn indicator. The altimeter is of the usual aneroid type.

The air speed meter, however, depends for its indication on the number of revolutions made by the generator, and consists of a frequency meter of the vibrating reed type. As the air speed changes the rate of rotation of the generator windmill follows, and thus the frequency of the current driving the gyroscope changes with the speed of the plane. The frequency meter

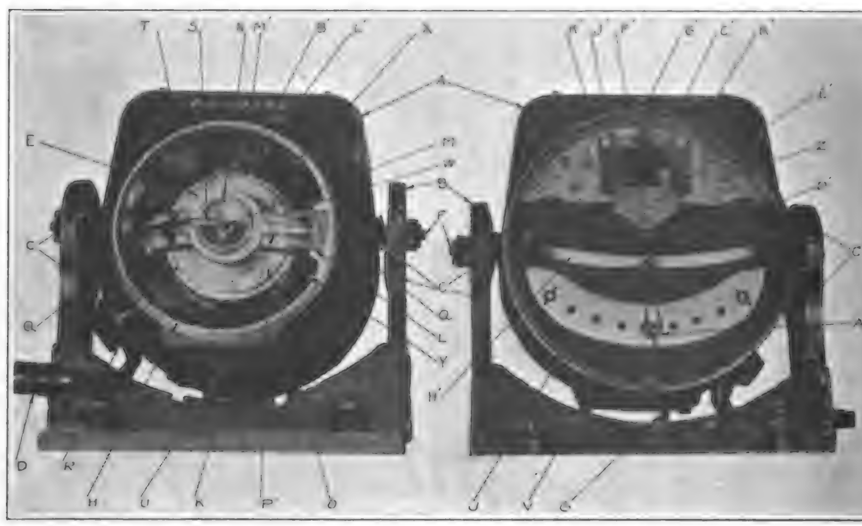

FIG. 18.—Drexler steering gauge.

is calibrated in kilometers per hour. Considerable lag is to be expected in a speed indicator of this type. The frequency obtained in normal flight should be about 300 cycles per second at the normal speed of the plane. This is obtained by adjusting the pitch of the windmill blades or changing propellers until the rotational speed is about 4,500 revolutions per minute.

When the generator is used merely to drive the turn indicator, it may be mounted either inside or outside the slip stream, but when used as a speed indicator it should always be mounted away from the effect of the slip stream.

DESCRIPTION OF TYPE KB.

The turn indicator mechanism shown in figure 18 is inclosed in a cast aluminum case (A) and is mounted in brackets (B), also of cast aluminum. A system of steel springs (C) tends to absorb small vibrations of the airplane. Four lugs with bolt holes are provided for securing the instrument. The armored cable leading to the generator is rigidly fastened by a nut (D) to the base, from which flexible wires run to the internal mechanism.

The case is carried on trunnions (F). A projecting fork (G) at the bottom engages a rod which acts as a pivot for the support holding the trunnions, thus preventing rotation of the case.

A pressed aluminum cover is screwed to a flange (H) at the rear of the case, while the front is closed by the glass held in place by an aluminum ring. The glass is packed by a tubular rubber gasket (J), which prevents breakage by vibration.

The case, with back and front covered, is practically tight against the weather, although water could enter if the instrument were submerged.

The main element inside the case is the gyroscope (E), which is mounted with its axis parallel to the longitudinal axis of the plane in a frame (K) free to turn only about an axis parallel to the transverse axis of the airplane. The angle through which this rotation or precession can take place is limited to less than 10° by a steel stop (L) screwed to the frame.

The gyroscope is the rotor of a three-phase alternating current induction motor revolving about a stationary field. The rotor is mounted on two annular ball bearings supported by a fixed steel shaft (M) through the hollow end of which pass the leads of the motor circuit. Two steel bushings (N), which screw into the aluminum frame (K), hold the shaft in position. Lock nuts prevent the shaft from turning in the bushings.

The gyroscope rotor (E) consists of a heavy steel rim (O) in which is secured a copper ring concentric with it and next to the pole faces of the stator.

Two metal disks, one on each side, are screwed to the rim and hold it in place. The outer ball races are mounted in the disks. All surfaces are finished and polished.

The precession bearings (Q) consist of steel bushings in the gyro frame bearing on hardened pivots with ball and point ends.

These pivots screw through the outer case and are held in position by lock nuts.

The motor leads enter through the outer case at (R), pass with a small amount of slack into a brass tube (S) screwed to the gyro frame which guides them to the hollow shaft (M) mentioned above.

Leads from one of the phases of the motor lines run to the primary coils of a small transformer (T) mounted in top of the case. The secondary coils of the transformer are connected through a small lamp bulb set in a recess below the gyro, supplying light on the scale and inclinometer tube. The lamp is reached through a small plate (U) screwed to the bottom of the case and is held in place between two spring contacts. A semicircular shaped piece of white translucent glass (V) is mounted directly in front of the lamp. The turn indicator scale is painted on the glass, and consists merely of three symbols denoting the center or zero and the two extremes, each side being divided into four sections by three round dots.

Precession of the gyro is transmitted to the pointer through the following mechanism: A vertical steel rod (W) connects the gyro frame to a system of diaphragms (X) which are mounted in the yoke (B′). A small steel plate screwed to B′ at (L′) has a slot which engages a hardened steel pin projecting from the pointer hub (M′). This pin is eccentric to the pointer bearings which are of the pivot type. Motion of the yoke (B′) thus causes a rotation of the pointer (A′), the whole mechanism being arranged in such a way that a turn to the right moves the pointer to the right.

The diaphragms (X), which are six in number, serve through their spring action as a centralizing device for the gyroscope. The system is supported on a brass angle which is inserted between the third and fourth cells and which is fixed to the back of the cast aluminum plate (Z). All six diaphragms are apparently filled with liquid, the three disks on each side of the support acting as reservoirs connected together by a small opening. When precession takes place the liquid flows from one reservoir to another giving a damping action similar to that of a dash pot.

The frame (K) is positioned on the rod (W) by two nuts each bearing on the frame through two springs (X) and hemispherical washers which fit into recesses. When the nuts are properly adjusted the gyro frame is centered in the stop (L). In one model the pointer may be set to zero position by lateral adjustment of the precession bearings. In model K B I, the latest available, the pointer is adjustable from outside the case by a screw which raises or lowers the diaphragm unit.

An arm attached to the pointer is fitted with a vertical slot whose center is on the pivot axis. A pin which holds the inclinometer bracket arm (C′) in place fits in this slot. When the pin is on the pivot axis no tilting of the inclinometer as mentioned above can take place. However, with the pin raised or lowered in the slot the inclinometer bracket (D′), which is pivoted

to the brass slide (E′) at (F′), is forced to tilt one way or the other. The up-and-down motion is produced by turning a screw (G′) from above. The thrust of the screw is taken by a flange bearing in a recess in the case. A stud (J′) on the slide which is held in place by two flat steel springs (K′) limits the vertical adjustment. Up or down motion of the slide (E) changes the position of the pin with respect to the axis of the pointer. The inclinometer (H′) which is held to the bracket (D′) by two steel spring clips is a liquid-filled tube of glass, curved concave upward with a steel ball in it. When the plane is in lateral equilibrium the ball should be in the center. The action is such that when the pin is above the center of rotation of the pointer the pilot must overbank the ariplane to keep the ball in the center of the tube.

No provision is made for oiling any of the bearings, but oil should be used sparingly on all contact surfaces and the ball bearings should be packed in light grease or vaseline.

Looking forward at the turn indicator, the gyro rotates counter-clockwise at a speed of 15,000 to 20,000 revolutions per minute.

The instrument should be mounted with the axis of precession horizontal, as otherwise pitching of the plane will show as a turn.

The wind-driven generator used for driving the turn indicator is of the three-phase rotating field type. The rotor, which is of rugged construction suitable for high speeds, consists of a cyclindrical iron core coaxial with the shaft, surrounded by a single circular magnetizing coil. At each end of the coil is a four-armed iron spider. The eight arms of the spider extend over the coil and intermesh so as to form alternate poles of opposite sign. Surrounding the rotor is the laminated stator wound with 12 coils from which run the 3 wires contained in the flexible armored lead to the indicator.

On the same shaft with the rotating field structure above described is the winding forming the armature of a direct-current generator which excites the field of the alternator. The field of the direct-current generator is bipolar and is carried on the same structure as the alternator stator.

The shaft also carries the commutator of the exciter and two collector rings to take the direct current to the rotating field of the alternator. The current flows in series through the latter and through the field circuit of the exciter.

The generator is driven under normal conditions about 4,500 revolutions per minute by a wooden fan or windmill whose pitch depends on the speed of the airplane. Generator speeds and voltages at various air speeds are tabulated below for windmills of 300 and 400 millimeters pitch.

TEST DATA.

Generator characteristics.—The generator speeds in revolutions per minute and voltages are tabulated for various air speeds. Two propellers were used, No. 1 of 300 millimeters and No. 2 of 400 millimeters pitch. The indicator was connected and running during the tests. On account of the rapid rate at which the voltage increased with the increasing air speed no tests were run at generator speeds over 5,000 revolutions per minute.

Propeller No. 1.			Propeller No. 2.		
Air speed.	Generator speed.	Voltage.	Air speed.	Generator speed.	Voltage.
12.7	1,000	....	18.6	1,090	2
17.2	1,460	2	27.9	1,860	6
23.1	2,125	7	38.5	2,625	12.5
32.4	2,910	14	46.0	3,190	17.0
38.4	3,405	20	51.1	3,450	23.4
41.5	3,640	26	54.4	3,750	33.0
42.6	3,700	28	58.1	3,990	53.0
45.4	3,875	48	58.3	4,050	69.0
46.3	3,960	62	60.4	4,225	....
49.3	4,200	73	63.0	4,325	....
51.9	4,385	87	63.2	4,335	76.0
53.9	4,525	....	64.7	4,460	81.5
....	....	....	67.4	4,630	....
....	....	....	69.1	4,760	96.5

As seen, the speed of the generator when driven by propeller No. 1 is about 31 per cent greater for the same air speeds than when driven by propeller No. 2. The air speeds corresponding to generator speeds of 5,000 revolutions per minute are 56 miles per hour and 73 miles per hour for propellers Nos. 1 and 2, respectively.

Calibration of turn indicator.—Laboratory tests showed that with a generator speed of 3,880 revolutions per minute the corresponding air speeds being 43.0 miles per hour for propeller No. 1 and 56.5 miles per hour for propeller No. 2, a rate of turn of 0.027 revolutions per minute gave a sensible deflection of the pointer. However, a rate of turn of 0.078 revolutions per minute was required to give a deflection sufficiently great for certainty of observation under practical conditions.

The necessary rates of turn for various rate deflections are tabulated below. The generator was driven at a speed of 4,100 revolutions per minute, which corresponds to that obtained at 60 miles per hour air speed.

Per cent scale deflection.	Complete turns (360°) per minute.
0	0.027 (or less)
25	0.51
50	0.89
75	1.29
100	1.70

Briefly, the air speed being 60 miles per hour, turns greater than 5.9 miles radius are not indicated, and turns of 0.31, 0.18, 0.12, and 0.094 miles radius correspond to pointer deflections of 25, 50, 75, and 100 per cent full scale, respectively.

No tests were made on the banking indicator.

FLIGHT TESTS.

Flight tests were made on the Sperry, Pioneer, R. A. E., and Drexler turn indicators.

The R. A. E. indicator has an unnecessarily large range of adjustment, that from points 6 to 10, inclusive, being of little use, due to the small movement of the pointer and the high centralizing force. Points 5 to 0, inclusive, give sufficient adjustment for all purposes. The Drexler has no sensitivity adjustment, but its damping action is such that its initial setting is satisfactory for all types of aircraft.

It was found desirable to mount the Venturi tube which drives the Sperry and Pioneer in the slip stream of aircraft of low speed range, while on faster machines, mounting in the air stream out of the propeller blast was satisfactory.

The R. A. E. should be mounted to get free air flow at the rotor, although the instrument functions when placed in disturbed flow behind a strut.

The generator of the Drexel instrument should be mounted outside of the slip stream particularly if it is also to be used as a speed indicator.

The Venturi-driven gyroscopes may also be connected to the intake manifold of the engine close to the intake port. This installation was tried on a Hispano-Suiza 180 horsepower and on a Liberty 400-horsepower engine. No interference in the functioning of the engines at speeds over 600 revolutions per minute was noticeable, although the Liberty at idling speeds of 200–300 revolutions per minute tended to fire irregularly in the three cylinders affected. If this installation is used a valve for closing the tube to the instrument should be provided for use in starting.

The degree of sensitivity desirable seems to depend more on the manœuverability of the plane than on its size and weight. It is probable that a turn indicator satisfactory for a small fast manœuvering scout will be satisfactory for all other types.

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AERONAUTIC INSTRUMENTS
SECTION V

POWER PLANT INSTRUMENTS

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SECTION V

POWER PLANT INSTRUMENTS

IN FIVE PARTS

AERONAUTIC INSTRUMENTS SECTION

Bureau of Standards

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REPORT No. 129.

POWER PLANT INSTRUMENTS.

PART I.

AIRPLANE TACHOMETERS.

By G. E. Washburn.

INTRODUCTION.

This report is Section V of a series of reports on aeronautic instruments (Technical Reports Nos. 125 to 132, inclusive) prepared by the Aeronautic Instruments Section of the Bureau of Standards under research authorizations formulated and recommended by the Subcommittee on Aerodynamics and approved by the National Advisory Committee for Aeronautics. Much of the material contained in this report was made available through the cooperation of the War and Navy Departments.

SUMMARY.

This part gives a fairly complete discussion of all the various types of airplane tachometers studied at the Bureau of Standards. French, German, and American chronometric tachometers are described in detail; also several types of foreign and domestic centrifugal tachometers. These types, chronometric and centrifugal, were those most extensively used by the Allied and Entente forces. In addition, a description is given of various tachometers of the electric, air viscosity, air-leak, magnetic, mercury viscosity, and liquid centrifugal types which have been used to some extent on aircraft.

USES OF AIRPLANE TACHOMETERS.

The airplane tachometer shows how fast the crank or propeller shaft of the engine is revolving. As a rule it indicates the revolutions per minute, or revolutions per minute of the shaft. It is driven usually by a flexible cable running from the engine to the instrument board.

The tachometer is often spoken of as the "revolution indicator," or "rev. indicator." Revolution indicators, however, show revolutions only, whereas tachometers show speed or rate of revolution.

Tachometers should be distinguished also from speedometers. The latter, though the same in principle, are used for a different purpose; namely, to show the speed of automobiles over the ground in miles per hour.

The principal use of the tachometer is as a detector of engine trouble. Engine trouble of any kind results in a slowing down of the engine. The tachometer, therefore, shows at all times, quickly and surely, whether or not the engine is working properly. The importance of knowing this is apparent, since an airplane depends on its engine, not only for propulsion but also for actual support or maintenance of level.

Tachometers are also used in adjusting the engine to its speed of greatest efficiency, and in performance tests.

Experienced aviators occasionally dispense with the tachometer as well as other instruments. To take the air, however, without first consulting the tachometer is to neglect a simple precaution and is foolhardy. In times of emergency the tachometer may be a great help, and, if working properly, is more reliable in all cases than the senses.

GENERAL INVESTIGATION OF AIRPLANE TACHOMETERS.

Apparatus was designed for investigating and testing tachometers under airplane conditions, such as vibration, change of temperature, and reduced air pressure. Detailed descriptions of apparatus and test methods are given in a later section of this report.

Type tests were made on six types of tachometers with the following results:

1. Chronometric tachometers, which measure speed by recording the amount of motion in a fixed-time interval showed exceedingly small errors throughout but had relatively low durability.

2. Centrifugals, in which the amount of deformation of a spring by centrifugal force indicates the speed, were not at all affected by reduced air pressure and not seriously by change of temperature. The calibration error and the lag were rather large and increased with continued running. Complete breakdowns, however, rarely occurred.

3. Air viscosity tachometers, which act by the viscosity of a thin air film between two concentric cylinders, were not much affected by reduced air pressure, but the temperature error was high. Heat caused an increase, cold a decrease in the reading. The calibration and lag errors were moderate.

4. Air pump tachometers, in which the speed is indicated by the pressure generated by an air pump operated at a speed proportional to the driving speed, were very seriously affected by reduced air pressure. The effect was nearly linear and about 20 per cent at one-half atmosphere (20,000 feet).

5. The magnetic tachometers, depending on the electromagnetic induction between a revolving magnet and a conducting drum or disk, were unaffected by reduced air pressure. They were, however, inaccurate in calibration, strongly affected by change in temperature and inconsistent with running.

6. The electric tachometers, consisting of a magneto used with a voltmeter graduated in revolutions per minute, had fair accuracy, but showed irregular fluctuations and a rather large temperature effect, besides being rather heavy.

Acceptance tests were made on about 300 instruments of the chronometric and centrifugal types, adoped by the Army and Navy, and taken from quantity production. As in the type tests, the chronometrics were found much superior in numerical errors, but inferior in endurance.

An experimental and theoretical investigation was made to improve the centrifugal type which, in view of its simplicity and freedom from breakdowns, seemed especially suitable for military use. A study was made also of master tachometers, of both old and new types, for accurate quantity testing and of special apparatus for rapidly calibrating the same.

TYPES OF AIRPLANE TACHOMETERS.

Airplane tachometers are the same in principle and construction as automobile speedometers; for the speedometer of an automobile, being connected to the forward axle of the machine, records primarily the speed of revolution of this axle and so is really a tachometer. However, because of the more severe conditions and requirements, there are fewer satisfactory types of airplane tachometers than of automobile speedometers.

Tachometers and speedometers are based on simple and well-known principles. Following is a classification of the various types of tachometers together with a brief statement of the principle on which each depends. Afterwards detailed descriptions of individual makes are given.

Chronometric or escapement tachometers.—The speed is measured by the motion of a gear (or toothed rack) in equal intervals of time during which it is connected with the main drive. Since the time intervals are equal, being regulated by an escapement mechanism, the motion of the gear during each interval is proportional to and, therefore, measures the average speed during the interval. The motion of the gear is shown by a pointer moving over a dial graduated in equivalent speeds of revolution.

CHRONOMETRIC TACHOMETERS.

FIG. 1.—Jaeger.

FIG. 2.—Van Sicklen.

FIG 3.—Hasler.

FIG. 4.—French Tel.

FIG. 5.—American Tel.

The pointer in instruments of this type is locked in position most of the time, changes in speed being indicated by sudden jumps at the ends of the equal time periods. This and the beating of the escapement mechanism, used to regulate the length of the time periods, are the distinguishing marks of this type of tachometer. Figures 1 to 5 show the exteriors of a few chronometric tachometers. Several instruments of this type are described in detail in the section entitled "Chronometric Tachometers."

Centrifugal tachometers.—Centrifugal force or the tendency of a body to fly away from the axis of rotation, which depends on the speed of rotation, acts against the elastic force of a spring. The amount of deformation of the spring determines the motion of the pointer and thus indicates the speed. The deflection, as distinguished from that of the chronometric instruments, is continuous, but in existing types, is not proportional to the speed. In liquid centrifugal tachometers the centrifugal pressure is balanced against hydrostatic pressure. Descriptions of a number of centrifugal tachometers are given in detail below in the section entitled "Descriptions of Centrifugal Tachometers."

Air drag or viscosity tachometers.—A cylinder geared to the main drive exerts a turning force on another cylinder concentric with the first through the viscosity of the thin air film between them. This force acts against a control spring deflecting the pointer by an amount depending on the speed. The deflection, like that of the centrifugals, is continuous, but not proportional to the speed. The Waltham type of air viscosity tachometer is described near the end of this part under the title "Air Drag or Viscosity Tachometers."

Air-pump or air-leak tachometers.—A pump, connected to the main drive, forces air into a chamber with a leak orifice. The pressure thus generated deflects a vane controlled by a spring. The deflection is read off on a scale graduated in corresponding speeds of revolution. A detailed description of the Van Sicklen speedometer is given later in this part under the title "Air-Pump or Air-Leak Tachometers."

Magneto or electric tachometers.—The electro-motive force or voltage of a magneto depends on the speed of revolution of the armature. Hence, a magneto used with a properly graduated milli-volt meter will show speeds of rotation. The Tetco electric tachometer is described in the section entitled "Magneto or Electric Tachometers," near the end of this part.

Magnetic tachometers.—A permanent magnet is revolved near an electrically conducting disk or drum mounted on the same spindle with the pointer and controlled by a spring. In virtue of the electric currents induced in the disk or drum a turning force is exerted on it which deflects it by an amount dependent on the speed. The deflection is read as usual on a scale suitably graduated in speeds of revolution. Two instruments of this type are described in detail near the end of this part under the title "Magnetic Tachometers."

Mercury viscosity tachometers.—The viscous drag of mercury rotating in a steel cylinder tends to carry with it a concentrically mounted steel disk and pointer. The force is balanced by means of one or more control springs. The deflection of the pointer is read on a scale suitably graduated in speeds of revolution. A description of the Atmo type of mercury viscosity tachometer is given later in this part under the title "Mercury Viscosity Tachometers."

Liquid centrifugal tachometers.—A paddle wheel is rotated in a liquid forcing it by means of centrifugal force through a valve into a system of vertical glass tubes. The height of the liquid column indicates the speed of revolution. A description of the Veeder type of liquid centrifugal tachometer may be found under "Liquid Centrifugal Tachometers" at the end of this part.

AMERICAN MILITARY AIRPLANE TACHOMETERS.

These are of the chronometric and centrifugal types. The magnetic type, used to a certain extent before the war, has been abandoned for the present.

These instruments, of whatever type or make, are required to be driven directly without adapter from the cam shaft of the airplane motor. They indicate, however, as stated above, the speed of the crank shaft or double the cam shaft speed. As a rule, therefore, American military airplane tachometers, if driven at a given speed, will indicate twice that speed.

VAN SICKLEN CHRONOMETRIC TACHOMETER.

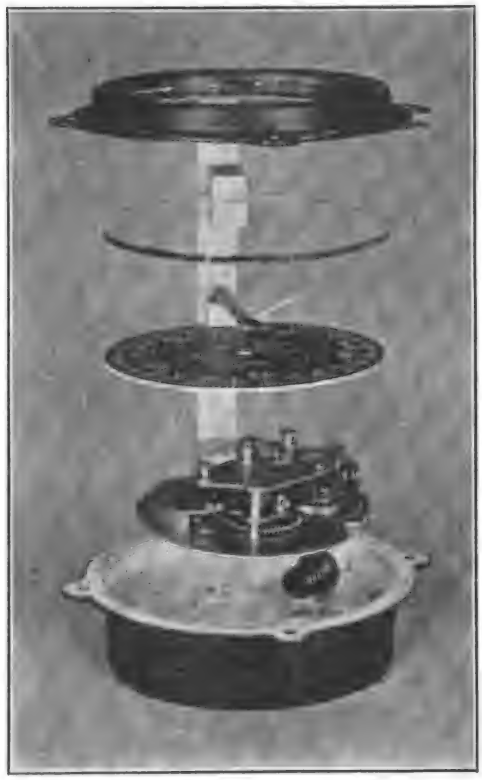


FIG. 6.—Case and Mechanism.

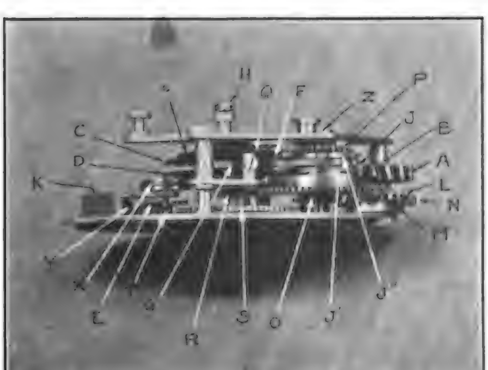


FIG. 7.—Mechanism—Side View.

FIG. 8.—Mechanism—Perspective.

Nevertheless, in certain cases, this requirement has been waived and the use of a gear box on the end of the cam shaft, between the cam shaft and the flexible drive, allowed. This arrangement gives greater steadiness, but the adapter is an added complication and undesirable.

The bezels and flexible shaft connections are for the most part standard, independent of type or make, so that instruments are interchangeable. The dials are graduated from 0, 300, 400, or 500 to 2,400, 2,500, or 2,600 revolutions per minute in intervals of 20 or 50 revolutions per minute. The figures on the dial denote hundreds of revolutions per minute. The 0, 5, 10, 15, and 20, as well as the tip of the pointer, are made luminous and the dial plate blackened for night reading.

In the following descriptions of individual makes those used on American airplanes are treated first and in greatest detail.

VAN SICKLEN CHRONOMETRIC TACHOMETER.

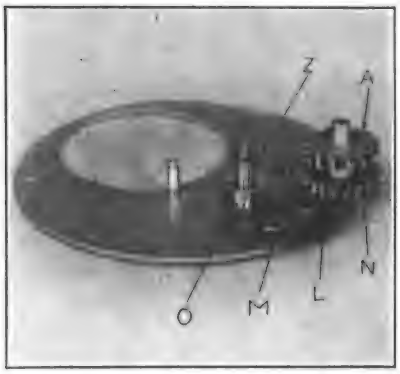


FIG. 9.—Drive System.

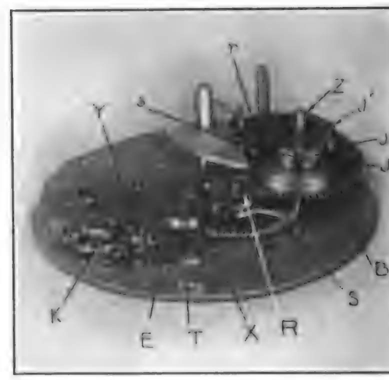


FIG. 10.—Escapement—Cam System.

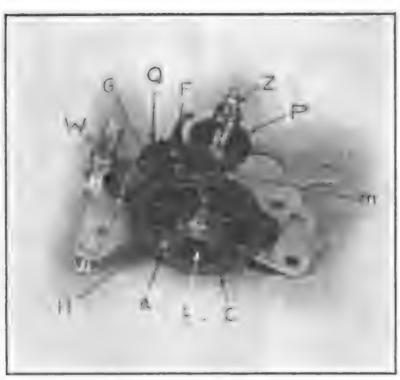


FIG. 11.—Counting System.

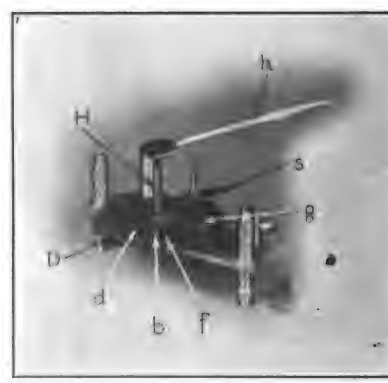


FIG. 12.—Indicating System.

CHRONOMETRIC TACHOMETERS.

Van Sicklen.—This instrument, "Type C" of the American military airplane tachometers, is a simplification and, in some respects, an improvement over the Jaeger chronometric tachometer described below. The complete instrument has already been shown in figure 2. Figures 6 to 8 show the case and mechanism. The gear referred to above, which is connected with the engine for equal intervals of time and the motion of which measures the speed of the engine, is the gear (C) called the counter gear. (K) is the escapement which regulates the length of time intervals.

The mechanism may be divided into the (1) drive, (2) escapement-cam, (3) counting, and (4) indicating systems (figs. 9 to 11). The drive system drives the counting and escapement-cam system. The escapement-cam system controls the operation of the counting and indicating systems. The motion of the counter gear is registered on the dial by the indicating system.

The drive system, figures 7, 8, and 9, begins with the main drive gear (A). It is composed of the gears (N), (L), (M), and (O). Its immediate purpose is to drive the spindle (Z) to which (O) is fixed and from which the counting and escapement-cam systems receive their motive power.

The gears (L) and (M) form a reversing mechanism which automatically provides for a rotation of (Z) in the same direction regardless of the direction of drive. This is necessary because the counting and escapement-cam systems operate in one direction only. The method of reversing is as follows: Gears (L) and (M) are mounted on a rocker arm pinned in the center in such a way that when gear (A), and consequently (N), rotates in one direction clockwise as seen in figure 8, (L) meshes with (O) and (M) idles without meshing with (O). When, however, (A) rotates in the opposite direction, (M) meshes with (O) and (L) merely drives (M) idly. (O) and (Z) rotate in the same direction in either case.

The escapement-cam system, figures 7, 8, and 10, is composed of the cams (J), (J′), and (J″), the toothed barrel (B) to which the cams are fixed, the gears (R), (S), and (T), the fly (E), and the double-roller escapement (K).

(B) receives from (Z), as described below, the motive power for the system. (R), (S), (T), and (E) transmit this power to the escapement which is driven thereby and allows the entire system, including the cams, to move suddenly at regular intervals. The operations of the counting and indicating systems, which are controlled directly by the cams, thus occur in a definite time order.

The releasing is done through (E), which engages a star pinion (Y) on the same pivot with the escape wheel. (E) has two arms and rotates through 180° at each release. The force of impact of the fly is lessened by the inertia wheel (X), which grips by friction the pivot to which (E) is attached.

The motion of the system being fixed, and that of (Z) variable, a slip drive must be used. This is in the form of a spring, called the mainspring, coiled up tightly inside of (B). The inner end of the spring is fastened to (Z). (B), on the other hand, idles on (Z) and also has no rigid connection with the spring. Consequently, as (Z) revolves, the spring slips around in (B). It exerts, however, on (B), through the friction caused by its tendency to uncoil, a turning force which drives the system. This force acts instantly when the instrument is started and continues at all driving speeds. The counting system, figures 7, 8, and 11, consists of the gear (Q), the fine toothed pinion (F) fixed to (Q), and the counter gear (C). The system is driven by the gear (P) fixed to (Z) and meshing with (Q). (F) and (Q) are mounted on a rocker arm (G), which the cam (J) causes to oscillate about a pivot (W) toward and away from (C). (F) is thus thrown alternately into and out of mesh with (C). (Q), however, remains in mesh with (P). The effect is, therefore, to put (C) successively into and out of connection with (Q) and hence with the main drive (A).

This occurs at regular intervals, in fact every second, since (J) is equally spaced and moves, as pointed out above, at regular intervals. The angle, through which (C) is rotated during each second is, therefore, proportional to the speed during the second. (C) is provided with a control spring (*c*) and a projecting stud (*a*) on its upper and under sides respectively. It is locked and released by the toothed pawl (*r*) operated by the cam (J″).

The indicating system (figs. 7, 8, and 12) is formed by the so-called pointer gear (D), similar to and below (C), the pointer spindle (H), to which (D) is fixed but on which (C) idles, the floating arms (*f*) and (*g*) pivoted on (H) between (C) and (D), and the pointer (*h*). Locking and releasing of (D) is accomplished by a toothed pawl (*s*) similar to and directly below (*r*) and operated by the cam (J). Unlike (C), (D) has ratchet instead of V teeth and can move forward while in contact with (*s*). It is provided with a control spring (*d*) similar to (*c*) and a projecting stud (*b*) on its upper side.

(*b*), (*f*), (*a*), (*g*), and a fixed stop (*m*) on (G) are arranged so as to engage each other in the order named. The engaging of (*a*), (*g*), and (*m*) stops (C) in a certain position. The engaging of (*b*), (*f*), and (*a*) holds (C) and (D) fixed with reference to each other.

The use of the floating arms (*f*) and (*g*), instead of direct contact of (*a*), (*b*), and (*m*), enables nearly two complete revolutions of (D), thus making a full circumference dial possible and insuring against injury in case of overspeeding.

When the instrument is idle, the control springs (*c*) and (*d*) cause (*b*), (*f*), (*a*), (*g*), and (*m*) to engage in the above manner. (C) and (D) thus assume definite zero positions.

In the operation of the instrument (C) and (D) are rotated away from (*m*) against the force of their control springs by (F) which drives (C) and hence (D) through the engaging of (*a*), (*f*), and (*b*). They are rotated back toward (*m*) by their control springs. By means of (*r*) (C) may be held when out of mesh with (F). Similarly (*s*) serves to hold (D) independently of (C). (C) turns back and forth continuously, returning to its zero position at regular intervals. (D), however, turns only when a change in speed occurs, forward for an increase, backward for a decrease.

If (D) is not in the zero position with reference to (C), that is, the position in which (*a*) and (*b*) are in contact with (*f*), it will always move back into that position, when free to do so, by the action of its control spring. The angular deflection of (D) and (*h*) from their zero positions is then equal to that of (C), which, as seen, is proportional to the speed. Accordingly, so long as the period of the escapement does not vary, the scale of this instrument is uniform.

The cycle of operations is determined by the cams (J), (J′), and (J″). At the start (C) is in its zero position and unlocked. (D) and (*h*) are locked in the position which they assumed in the preceding cycle. (F) meshes with (C) for one second, turning it through a certain angle. According as the speed is (1) the same as (2) greater than or (3) less than in the last cycle, (C) (1) just reaches (D) or (2) engages (D) and pushes it forward or (3) stops short of (D). In any case (*r*) locks (C) in its extreme position, (*s*) then releases (D), allowing it in case (3) to assume the zero position relative to (C). Next (C) is again released and returns to its zero position. The cycle then repeats itself.

The pointer (*h*) follows the motions of (D). It is locked at a reading equal to the speed during a given second of mesh of (F) with (C) from the end of that second to the end of the next. It then moves forward or backward suddenly by an amount equal to the change in speed. This instrument, like others of the chronometric type, therefore, deflects intermittently, indicating the average speed over an interval of time rather than the speed at each instant.

The scale is closed and graduated from 0 to 2,500 revolutions per minute in intervals of 20 revolutions per minute. The instrument is driven directly from the cam shaft without adapter.

Compared with foreign chronometrics, the Van Sicklen has only one counter gear, the reversing mechanism is simpler and the escapement of considerably smaller size. The first is a simplification, but necessitates the instrument remaining idle for part of the time. Worth mentioning is the method of fastening the pointer which is driven onto a square boss and held by a spring washer to prevent slippage from the sudden jumping of the pointer in tachometers of the chronometric type.

Tel.—This instrument, used by the American military forces and known as "Type A," is shown in figure 5. It is a copy of the French instrument shown in figure 4. Figures 13 to 16 show the mechanism. It contains drive, escapement, counting and indicating systems which perform the same functions as in the Van Sicklen. However, the counting member is a toothed rack instead of a gear. Also, the driving and locking devices are not brought into connection with the counter, but the counter with them by a motion at right angles to its counting motion.

The drive system, figure 17, consists of the main drive gear (A), fastened to the arbor (S) and meshing with a pinion on the drive spindle of the instrument, the gear (N), also attached to (S), and the gears (L), (M), (O) and (P). Its function is to turn the spindle (Z), figures 18 and 19, to which (P) is fixed and from which the counting and escapement systems are driven.

(Z) must revolve in the same direction independent of the direction of drive. This is accomplished by means of a reversing mechanism formed by the gears (N), (L), (M), and (O). (L) and (M) are mounted on a rocker (T), idling on (S), and are in permanent mesh with (N). (O) is pivoted on a stud fastened to the frame and is in mesh with (P). According as (A)

rotates clockwise or counterclockwise, the friction between (S) and (T), which is increased by the slip spring (D), rotates (T) slightly one way or the other and causes (L) to mesh with (P), (M), and (O) idling, or (M) with (O), (L) idling. The direction of rotation of (P) is the same in either case. The screw head (E), playing in the slot (G), serves as a stop for (T).

The escapement system (fig. 18) is composed of the toothed barrel (B), the shaft (J), and the double-roller escapement (K). (J) has fastened to it at one end the gear (R) meshing with (B), at the other end the escape wheel (U). The motive power for the system, which is applied, as in the Van Sicklen, by means of a slip spring, called the main spring, fastened to (Z) and coiled up inside of (B), is transmitted through (P) and (J) to (K), which releases it and allows the system, including (J), to move suddenly at regular intervals. The time for one

TEL CHRONOMETRIC TACHOMETER.

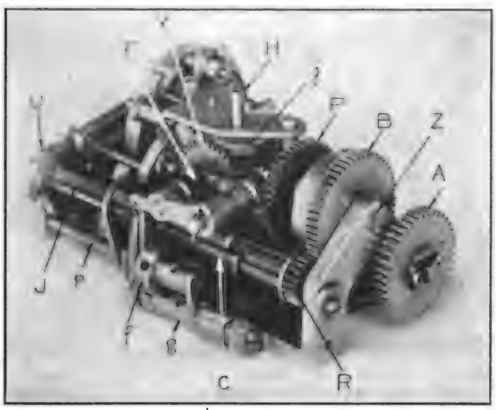


FIG. 13.—Perspective.

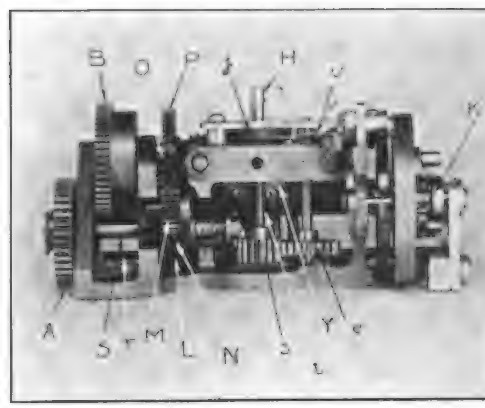


FIG. 14.—Side View.

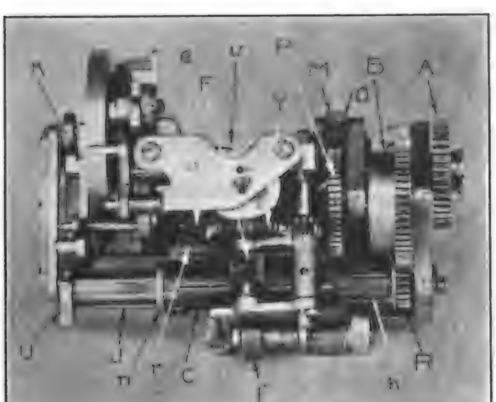


FIG. 15.—Top View.

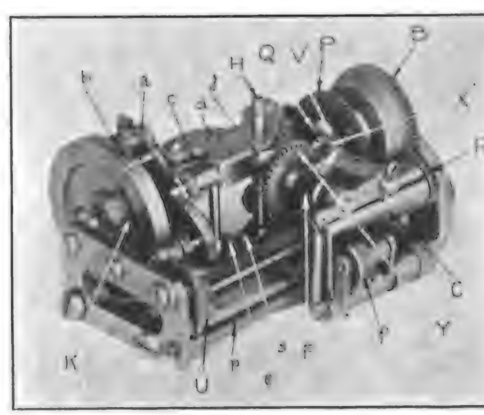


FIG. 16.—Perspective.

swing of the balance wheel is one-quarter second and 12 swings are required for a complete revolution of (U). (J) thus makes a complete revolution in three seconds in steps of one-twelfth of a revolution every quarter second.

The escapement, as seen, is very heavy. To facilitate starting, it is fitted with an auxiliary device which stops it shortly after the instrument is stopped, thus preventing the mainspring from unwinding completely, and also stops it off center with tension in the escapement spring. The arrangement is such that, when the pointer returns to its zero position, a pin (*a*) falls automatically, engaging a stud (*b*) on the rim of the balance wheel and stops the escapement. The movement of (*a*) is accomplished through a pin (*c*) which drops into a slot in the upper end of the arbor (*d*) connected to the pointer staff (H) through the gears (*e*) and (*s*).

The counting system, figure 19. is made up of the fine-toothed pinion (F), connected with (Z) through the gear train (Y–X–V–Q), the toothed racks (C), and the cylindrical pawl (*f*). The racks, in the form of three identical cylindrical arcs of 120° each, envelop the shaft (J) along which they are free to slide in grooves. Their zero position is against (R), which position they tend to assume by the action of the helical control springs (*h*) lying in grooves and fastened respectively to (J) and to the racks. (F) and (*f*) are held in contact with the racks by the springs (*k*) and (*m*) attached to the rockers (*q*) and (*g*) in which they are mounted.

As (J) rotates, clockwise viewed from the escapement end, each rack is successively (1) engaged by (F) and carried, by its rotation, along (J) from (R) toward (U) against the force of its control spring; (2) caught and held by (*f*) in the position in which it is left by (F); (3) disengaged from (*f*) and drawn back to the zero position by its control spring.

TEL CHRONOMETRIC TACHOMETER.

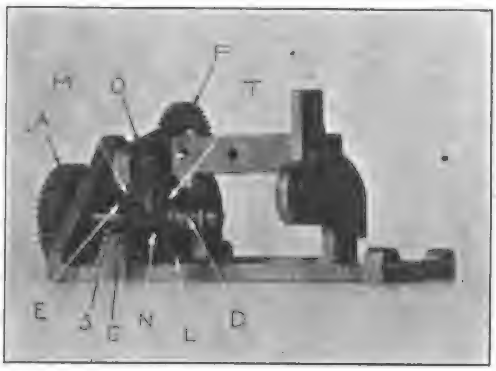


FIG. 17.—Drive system.

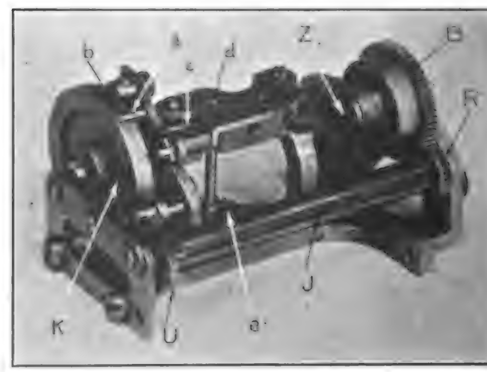


FIG. 18.—Escapement system.

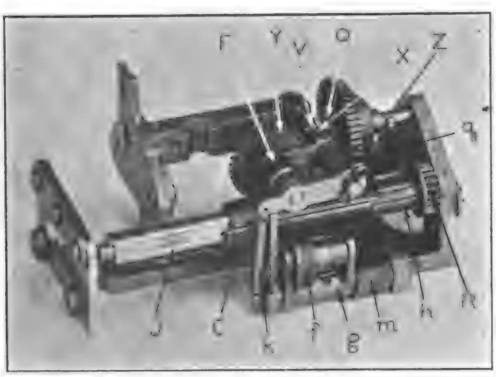


FIG. 19.—Counting system.

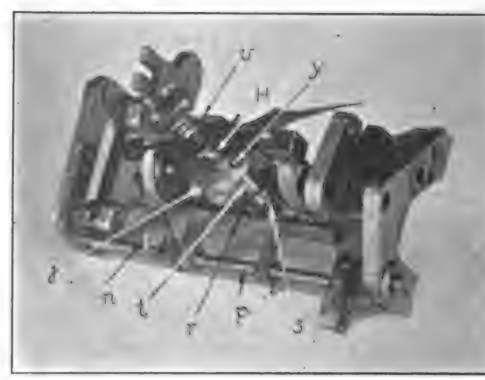


FIG. 20.—Indicating system.

Since the distances between the points of contact of (F) and (*f*) and the width of the racks are each 120°, the above operations follow each other without interruption or overlapping, have each one second, a third of the period of revolution of (J), allotted to them and are performed by the racks with a successive phase difference of one second. Consequently one of the three racks is engaged in each of the three operations at every instant and the instrument is never idle.

Now (F), being geared directly to (Z), and hence to the main drive (A), rotates at a speed proportional to the driving speed. Also, as seen, the period of mesh of the racks with (F) is constant and equal to one second. Therefore, the distances the racks are moved along (J) are proportional, so long as the escapement is unaltered, to the speed during successive seconds. Thus, the rack which is held by (*f*) during each second is at a distance from the zero position of the racks proportional to the speed during the preceding second.

The indicating system, figure 20, is formed by a collar (*n*) encircling (J) loosely, a toothed rack (*r*), which slides on a rod (*p*) and to which (*n*) is attached, and a gear (*s*) fixed to the pointer staff and meshing with (*r*). The racks, as they travel along (J), engage (*n*) and thus move (*r*), (*s*), (H) and the pointer. A control spring (*t*) opposes the motion taking up the backlash between (*r*) and (*s*) and keeping (*n*) in contact with the racks.

(*n*) rests, in its zero position, against all three racks in their zero position and, during each second, as the instrument operates against the rack held by (*f*) in that second. The displacement of (*n*) and (*r*) from their zero position is, therefore, the same as that of the rack and hence proportional to the speed during the preceding second. (*r*) and (*s*), however, constitute a simple rack and pinion, so that the angular displacement of (*s*) and of the pointer from their zero positions is proportional to the linear displacement of (*r*) and thus proportional to the speed. This instrument, therefore, has a uniform scale.

It does not, however, show the speed at each instant, but the average speed for periods of one second. It indicates throughout a given second the average speed during the preceding second. Then at, or very near, the end of the second the reading changes suddenly to the value for that second. This reading is maintained for the next second and so forth.

Changes in reading take place at the ends of the second periods because it is then that (*n*) shifts from one rack to another. If an alteration in speed occurs, the succeeding rack either (1) stops short of the preceding rack, which is in mesh with (*f*) and against which (*n*) is resting (decreasing speed), so that, when the latter is released, (*n*) is drawn backward by (*t*) into contact with the former; or (2) engages (*n*) a little before the close of the second (increasing speed), lifts it off the end of the preceding rack and pushes it forward suddenly, holding it on coming to rest. In both cases the change in reading is abrupt and occurs practically at the end of the second period. If the speed is constant, each succeeding rack stops just abreast of the preceding one and no change in the position of (*n*) or the pointer occurs.

A loose pin-and-hole connection (*y*) (figure 20) inserted between (H) and the pointer serves to remove fluctuations of the latter due to imperfect mesh of the racks with (F) and (*f*) at the expense, however, of accuracy and sensitivity. The spring (*y*) bearing in the threaded rim of the disk (*j*) acts as a damper for this arrangement and, by the dropping of its curved end into a slot in the disk, as a zero lock for the pointer. The threads prevent this action at full scale deflection.

The maximum possible lag in this tachometer, between a change in speed and its indication on the dial, is seen to be one second.

The dial is graduated in identical manner with that of the Van Sicklen and the instrument also runs without adapter.

Jaeger.—This instrument has already been shown in figure 1, and in figures 21 to 23 are perspective, top, and side views of the mechanism.

The Jaeger, widely used on French airplanes, is an intricate and beautifully made chronometric of the gear type, to which the Van Sicklen is closely related. Unlike the latter, however, it has two counting gears (C) and (C′) and thus operates continuously. The mechanism conforms to the usual chronometric type. The drive is through a crown wheel (A) engaged by a pinion bearing in the case of the instrument. From (A) through a reversing mechanism, considerably more complicated and delicate than that of the Van Sicklen or TEL, the rotation is transmitted to the spindle (Z) and to the fine-toothed pinions (F) and (F′) which are thrown into and out of mesh respectively with (C) and (C′) at regular intervals. From (Z) the escapement (K) and the cams (J) are driven through the usual spring and barrel (S.) The pointer gear (D) is midway between (C) and (C′) and these gears have corresponding to them the three locking arms (L). Between (D) and the pointer staff is a loose pin and hole connection similar to that in the TEL and serving the same purpose.

The method of meshing and unmeshing (F) and (F′) with (C) and (C′) is somewhat different from that employed in the Van Sicklen. Namely, the spindles to which (F) and (F′) are fastened bear at their upper ends only in the oscillating rocker (G). The lower ends have fixed

JAEGER CHRONOMETRIC TACHOMETER

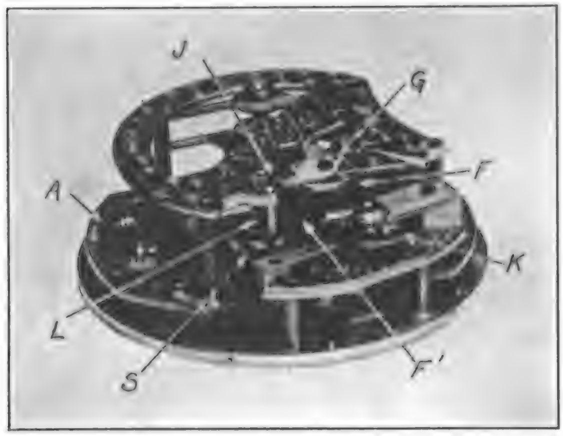


FIG. 21.

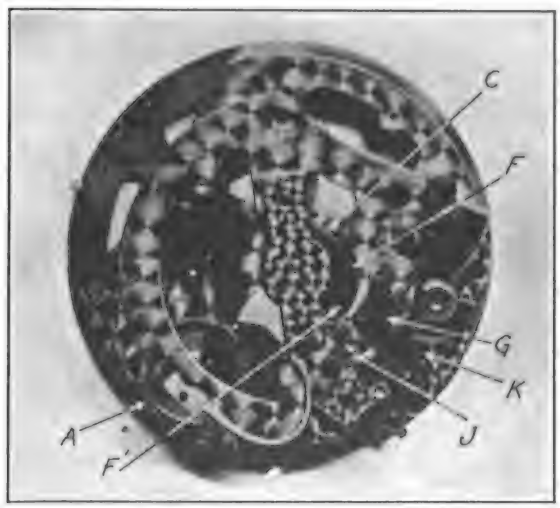


FIG. 22.

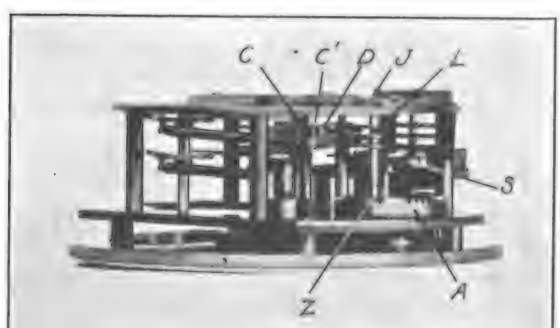


FIG. 23.

bearings in the frame of the instrument, about which as centers the spindles and gears swing, due to the motion of (G). Thus (F) and (F′) are thrown into and out of mesh with (C) and (C′). The driving pinions are fastened to the spindles close to their lower ends where the swinging motion is small, whereas (F) and (F′) are attached near the upper ends and so have considerable motion.

The escapement is about as heavy as in an ordinary alarm clock and of the double-roller type. The balance wheel bearings are jeweled. The escape wheel spindle has a light spring bearing against it to prevent rotation backward during the interval between release of one fly arm and contract with the other arm, which would cause irregularities in the counting periods.

The control springs in this instrument are helical or flat plate springs and act indirectly through toothed sectors and pinions on their respective spindles. The counter gear sectors have slender flat springs lying in slots in their faces. These are provided at their free ends with teeth which project beyond the sector teeth at the point of mesh with the pinion on the counter-gear spindle when the instrument is at rest. By the action of the springs these teeth mesh tightly with the pinions and thus eliminate backlash which, owing to the resulting uncertainty in the zero position of the counter gear, may cause a considerable error in reading of the instrument.

Stover-Lang.—The counting element in this tachometer is a radial arm which is lowered at regular intervals into mesh with a rotating crown wheel geared to the main drive spindle. An auxilliary arm, interposed between the counter and the pointer system, is arranged to drop back into contact with the counter shortly before the end of the counting period. It is then carried forward by the counter during the remaining motion of the latter and is held in the extreme position of the counter by ratchet action. The pointer system is then released and assumes the position of the auxiliary arm. The counter itself is not locked at all. The escapement is of alarm-clock size and unjeweled.

The instrument has been arranged for use with an air drive consisting of a diaphragm operated by an eccentric fixed to the rotating shaft. This diaphragm gives puffs of air with a frequency equal to that of the rotation which, being transmitted to the instrument through a tube, operates a ratchet engaging the main drive gear of the mechanism.

This form of drive is free from many defects of the flexible cable, but is intermittent in its action, and as yet has been adapted to chronometric tachometers only.

Hasler.—This instrument, shown in figure 3, is a hand chronometric suitable for tests on airplane motors and other tachometers.

The escapement functions only when one of the two push buttons seen projecting from the edge of the case is pressed and released. Furthermore, it marks off but one period, three seconds in length, during which the counter is connected with the main drive and the pointer carried through a certain angle proportional, as usual, to the speed. The pointer is locked automatically in its final position and the speed is read off. Resetting of the pointer is accomplished by means of the other push button. Ten revolutions of the pointer, giving a total range of 10,000 revolutions per minute, are provided for.

Bruhn.—This instrument, shown in figures 24 to 27, is a German chronometric of the gear type. It is very similar in design to the French Jaeger and the American Van Sicklen.

Like the Van Sicklen, it has only one counting gear; the counting period, however, is one-half second, thus giving a resetting of the pointer at the end of each second. The drive is through a bevel gear meshing with the gears (A), figures 25 and 26, which are arranged in such a way as to idle when driven in one direction and drive through to the gear fixed to the spring barrel (B) when driven in the opposite direction. The barrel (B) is always driven in the same direction for either rotation of the drive gear.

The drive continues from (B) through a coiled slip spring to the staff (S), escapement (K), and back to the cams (J), which control the meshing of the counting pinion (F) with the counting gear (C), and also the operation of the holding pawls (P) for the counting gear (C), and (M) for the pointer gear (C′). There are three pawls (P) and two (M), the pawls (P) being spaced one-

third of a tooth out of phase with each other and the pawls (M) one-half of a tooth out of phase. The escapement (K) is of the double-roller type, unjeweled, and much more rugged than that of either the Van Sicklen or the Jaeger.

A noteworthy feature is the addition of the two odometers (L) and (O). (L) is driven through a train of gears from the staff on which the cams (J) are fixed and shows the number of hours which the instrument, and therefore the engine, has run. (O) is connected to the drive gear, and its readings, multiplied by 100, give the total number of revolutions which the crank shaft of the engine has made.

BRUHN CHRONOMETRIC TACHOMETER.

FIG. 24.

FIG. 25.

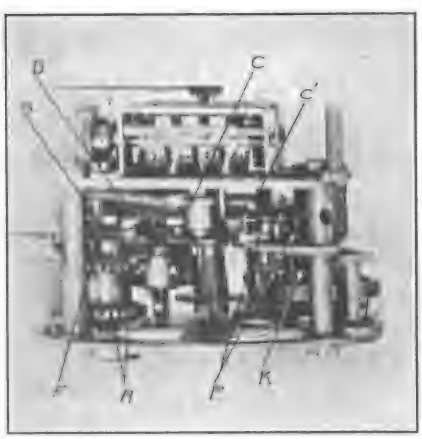


FIG. 26.

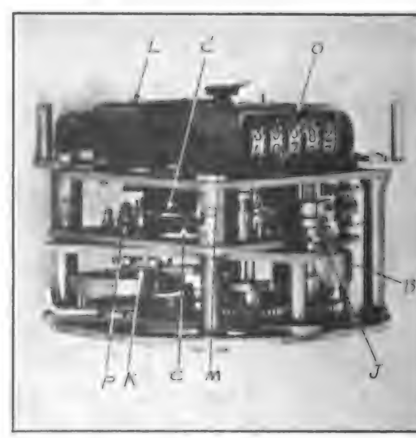


FIG. 27.

CENTRIFUGAL TACHOMETERS.

TYPES OF CENTRIFUGAL TACHOMETERS.

The most common types of centrifugal tachometers are the so-called governor and oblique-weight types.

The governor type is thus named because of the resemblance of the rotating part to an ordinary engine governor. It consists, namely, of a shaft (A), (fig. 28), with a set of weights (B) grouped about it which, as the shaft rotates, act by centrifugal force on a control spring (E). The shaft (A) is hardened and polished, and is mounted vertically and centrally in ball bearings either in the case of the instrument itself or in a separate frame. The weights (B) are attached by links above to a spider (C) fixed to the shaft and below to a grooved collar (D), free to slide along the shaft. The spring E, which is helical, encircles the shaft between (C) and (D).

When the system rotates, the weights (B) pull outward on the links. (D) is thus drawn up the shaft and (E) is compressed. Ultimately, for a fixed speed, the weights and (D) assume a definite position in which the centrifugal force is just counterbalanced by the elastic force of the spring. The motion of (D), which is small ($\frac{1}{4}$ to $\frac{3}{8}$ inch), is magnified and changed into a pointer motion by the indicating train, consisting of the pin (F) bearing on (D), the toothed sector (G), and the pinion (H). The spring (J) on the pointer staff keeps (F) in contact with (D) and also takes up the backlash between the sector and pinion.

In the oblique-weight type, shown diagrammatically in figure 29, the rotating element consists of a weight or frame (B) encircling the main shaft (A) and free to rotate about a spindle (C) fixed perpendicularly to (A). In the position of rest (B) is oblique to (A), but when rotating tends to rotate about (C) into a position perpendicular to (A). This motion is opposed by a control spring (E), so that at each speed a definite position is reached in which the centrifugal couple exerted by (B) is just balanced by the restoring torque of (E). Thus the motion of (B), imparted to the pointer through a suitable indicating train, such as shown in figure 30, gives an indication of the speed. The double oblique-weight type has two crossed weights pivoted on the same axis and placed symmetrically about the shaft.

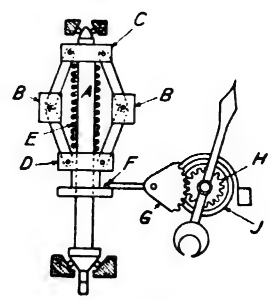


FIG. 28.—Governor type.

Other forms of centrifugal tachometers not belonging to the above types will be pointed out in the discussion of individual makes, together with various modifications of the control spring and indicating train.

Centrifugal tachometers used on American airplanes are all of the governor type, but the governor weights differ in size. This necessitates a difference in the running speed, since the control springs and indicating trains are practically alike. The light governors, therefore, must run at higher speed than the heavy ones to give the same deflection. In all cases, however, the speed of the governor is equal to or greater than the indicated or crank shaft speed; that is, equal to or greater than twice the driving or cam shaft speed. Consequently gears giving an increase in speed of one to two or more are necessary. The speed of the governor relative to the indicated speed and the location of the gears, whether within the instrument or in a special adapter on the end of the cam shaft, are pointed out in each case below.

The oblique-weight type, though extensively used abroad, especially in England and Germany, has not yet been adopted in America for use on airplanes.

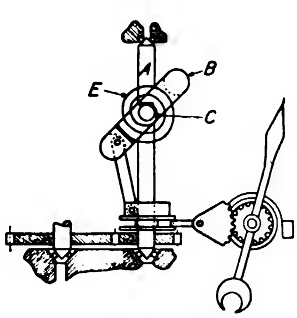


FIG. 29.—Oblique weight type.

Johns-Manville.—This instrument, shown in figure 30, is "Type B" of the American military airplane tachometers. It is of the heavyweight slow-speed type, the governor running at indicated or crank shaft speed. The speed ratio between the cam shaft and the governor is, therefore, one to two. The gears for accomplishing the change in speed are in a separate adapter on the end of the cam shaft, since it was thought, from experiments on sample instruments, that too great unsteadiness would result if they were placed in the instrument itself. Later, however, a model was designed with the gears in the instrument, but this was not produced extensively.

The governor has three weights of special shape which touch when at rest, forming a continuous girdle around the shaft. The ball bearings are contained in the case itself, the upper one being adjustable, the lower one fixed. This is because the weight of the governor falls on the lower bearing.

The indicating train, seen at the left in figure 30, is of the type shown in figure 28 and is carried by a bridge spanning the front of the case. The contact piece which bears on the sliding collar is a pivoted shoe of hard fiber. This is believed to wear better than steel and to be less apt to scratch the surface of the collar. The arm carrying the fiber shoe is adjustable on the spindle on which it rotates, but is not adjustable in length. The pointer is driven on to the tapered end of the pointer staff, and so is also adjustable. Calibration is accomplished by resetting and bending the shoe arm, adjusting the pointer, and deforming the control spring.

The scale is graduated from 400 or 500 to 2,500 or 2,600 revolutions per minute, respectively, in intervals of 50 revolutions per minute and has an angular length of about 190°.

Jones "Victometer."—This instrument, shown in figure 31, is used almost exclusively by the Navy. It has very light weights and the governor runs at twice indicated or four times driving speed. The gears having this latter ratio are contained in the instrument itself as seen in the figure.

The ball bearings are set in a ringlike frame of which the bridge carrying the indicating train is an integral part and to which the dial plate and bezel are fastened. The case proper is a thin detachable metal cup which slips on over the back of the frame. This arrangement makes the governor and indicating train very accessible and permits calibration with the dial in place.

AMERICAN CENTRIFUGAL TACHOMETER.

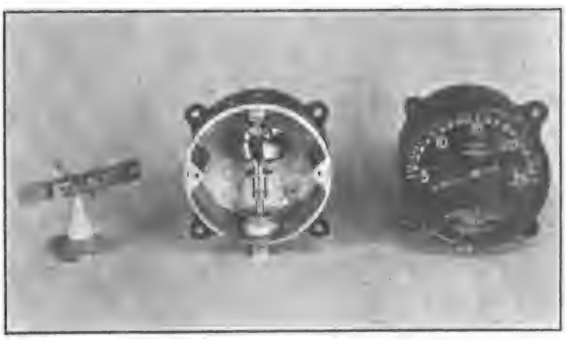


FIG. 30.—Johns—Manville.

FIG. 31.—Jones.

FIG. 32.—Reliance.

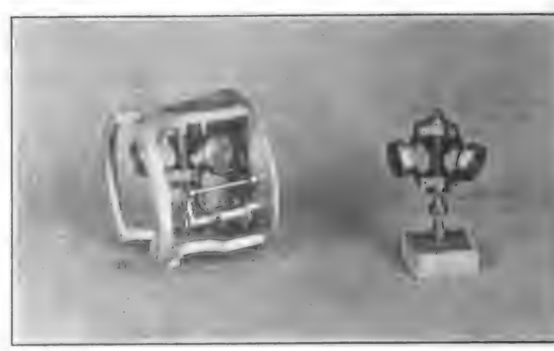


FIG. 33.—Hoffecker.

There are three weights. The spider to which the links are attached at the top is adjustable, being held by a set screw.

The indicating train is of the type shown in figure 28. The lever carrying the contact pin is, however, adjustable in length. The contact pin is of steel. The pointer is driven into a tapered staff, as in the Johns Manville.

Reliance.—This tachometer, used by the Navy, appears in figure 32. It also is of the light-weight high-speed type. The governor speed is about one and a half times indicated speed or three times cam-shaft speed. A special adapter is used on the cam shaft, there being no gears in the instrument itself.

The indicating train is also of the type shown in figure 28.

The contact pin is of hardened steel, the sliding collar being of brass. An adjustable contact pin lever and an adjustable zero stop are provided for use in calibration.

The governor bearings, indicating train, and dial are mounted on a detachable frame, so that the calibration may be done before inserting in the case with good access to the mechanism.

This instrument has not been standardized. The shaft connection as made is provided with a sliding element which a compression spring keeps in mesh with the flexible shaft. Thus also the end thrust in the flexible shaft, which may cause unsteadiness, is taken up.

The dial is white and the scale, determined separately for each instrument, extends from 200 to 2,400 revolutions per minute in intervals of 50 revolutions per minute over an angle of about 225°.

The case and mechanism are both of heavy construction.

Hoffecker.—This instrument, shown in figure 33, is very similar to the Reliance. The weight and speed of the governor are about the same as well as the means of calibration.

The frame carrying the governor and indicating train is of rigid though light construction.

A unique feature of the indicating train is that it has two contact pins of hardened steel which form the tines of a fork swiveled on the end of the usual contact pin lever. These pins bear on opposite sides of the sliding collar and are intended to eliminate fluctuations due to lack of perpendicularity of the surface of the collar to the shaft or roughness of the surface.

The instrument has not been standardized. The flexible shaft provided has a ball bearing end and a wedge-shaped tip which facilitates meshing at high speed.

The scale is graduated similarly to that of the Reliance and likewise is determined separately for each instrument.

Jones speedometer.—This instrument, shown in figure 34, is of the oblique weight type with sliding collar, the weight being in the form of a ring. The connection between the governor and the sliding collar is formed by a lug projecting from the upper end of the collar sleeve and bearing on a hardened steel pin embedded in the oblique weight. There are two helical control springs—one, a weak spring which is compressed by the collar, the other, a strong clip-like spring which is coiled up as the oblique ring deflects.

The indicating mechanism is unusual in that it contains a cam plate, the proper shaping of which gives a uniform scale.

Schaeffer and Budenberg.—Figure 35 shows the exterior of the instrument, which is of the same type as the Jones centrifugal speedometer described above. The motion of the weight is transmitted to the collar through two parallel links pinned at their ends. A unique feature is that the contact pin bears against the under surface of the sliding collar.

The instrument has three drive spindles and is fitted with a gear box, so that full scale deflection may be had for three different speeds, such as 200, 1,000, and 2,000 revolutions per minute, by using the proper spindle.

This type of instrument is suitable for tests on airplane motors.

Elliott.—This is a British instrument, also of the oblique weight type, and is shown in figure 36. The governor is in the form of a dumb-bell pivoted in a boxlike frame inserted in the governor shaft. The control spring is a helical spring fixed to the frame at one end and to the governor at the other.

The indicating mechanism is unusually simple in that the lever carrying the contact pin is fastened directly to the pointer staff. The pointer is pivoted in the lower part of the dial and the angular motion is only about 90°. The scale is graduated from 800 to 2,000 revolutions per minute in intervals of 50 revolutions per minute.

Smith.—This instrument, the mechanism of which is shown in figure 37, is also a British tachometer of the oblique weight type. The governor is a flat link-like casting. A hemispherical casting, fixed to the lower end of the shaft, supports the ends of the governor pin and also serves as a flywheel. There are two exactly similar flat coiled control springs. The connection between the oblique weight and the sliding collar is formed by a fork fixed rigidly to the collar and bearing on a hardened pin, as in the Jones speedometer above.

The indicating mechanism is of the ordinary construction, shown in figure 28. The scale is graduated from 600 to 2,000 revolutions per minute in intervals of 20 revolutions per minute and has an angular length of about 300°.

FIG. 34.—Jones Centrifugal Tachometer.

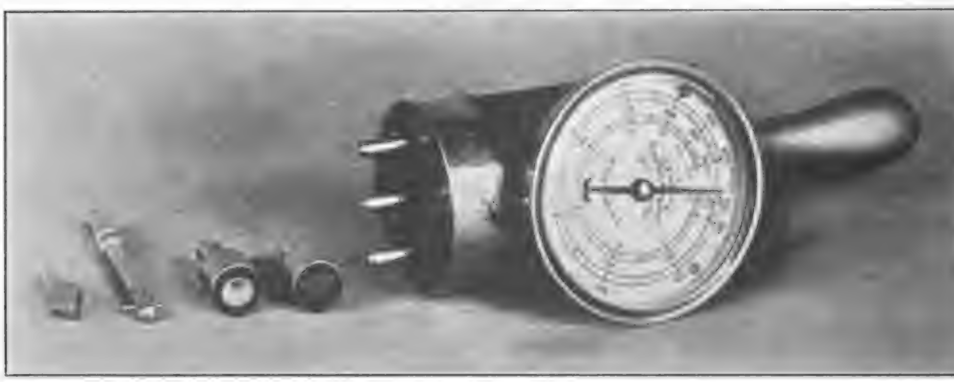


FIG. 35.—Schaefer and Budenberg.

FIG. 36.—Elliott.

FIG. 37.—Smith.

Oliver.—This tachometer, the mechanism of which is shown in figure 38, is of the oblique weight type, but has certain peculiar features.

Uniformity of scale is obtained by means of a cam plate in the governor. This cam is attached to the oblique weight and deflects with the latter. Connection between the cam and the indicating train is made by means of a rod sliding in a boring in the shaft. The contact point with the indicating train is in the center of the rod where there is no motion and thus wear is avoided. The contact point with the cam is near the axis of rotation of the oblique weight. This tends to minimize disturbances due to a reaction of the rod on the oblique weight.

The governor control consists of two pairs of helical tension springs. The points of attachment of these springs are so placed that the lines of action of the springs pass through the axis of rotation of the oblique weight in the position of rest. As the oblique weight deflects, however, they get farther and farther away from this axis. Thus a restoring torque increasing

FIG. 38.—Oliver centrifugal mechanism.

FIG. 39.—Olhovsky mechanism.

FIG. 40.—Olhovsky case.

more rapidly than the first power of deflection is obtained, which, it is claimed, facilitates the attainment of a uniform scale.

Olhovsky.—The Olhovsky tachometer shown in figures 39 and 40, is a Russian instrument of the double oblique weight type with sliding collar. The weights are in the form of rectangular frames consisting of cylindrical rods with flat connecting pieces and are in rotational balance. Each acts separately on the collar through a link. The control spring is helical and is located between the sliding collar and a ball-like shoulder on the shaft, being compressed as the collar moves upward.

A two-tined steel fork with swivel joint, similar to that in the Hoffecker described above, is used to connect the governor and indicating mechanism.

A noteworthy feature of this instrument is that it is compensated for the effect of tilting with reference to the vertical and also for the effect of external shocks. This is accomplished

by unbalancing the governor weights by an amount equal to one-half of the combined weight of the collar and floating pin and by pivoting the rollers at a distance from the centers of rotation of the weights equal to that of their centers of gravity. Thus the movement of the weights about their pivots, due either to gravity or sudden acceleration in any direction, is just counterbalanced by that of the collar and pin.

The indicating mechanism is novel. A nut with a hardened steel point bears on the float mentioned above. Longitudinal motion of this nut causes the threaded pointer spindle, which is screwed into it, to rotate. A coiled spring on the pointer staff serves as a control spring for the governor as well as to take up backlash.

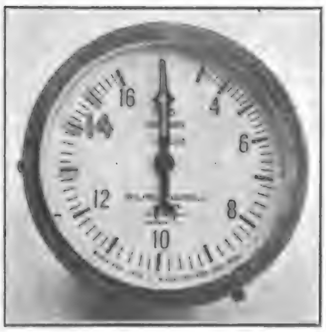


FIG. 41.—Morell "Phylax."

The instrument is very compact, the whole mechanism being contained in a cylindrical case 2¼ inches diameter by 2 inches high.

Morell "Phylax."—This instrument, a single oblique ring type of German design, is shown in figure 41. It is of the usual link and sliding collar construction. As in the Jones speedometer there are two control springs, one compressed by the collar and the other a clip-like spring between the governor and the shaft.

The indicating train is unique in that it contains a spring which serves to take up sudden shocks or changes in speed. It is also provided with an air damping device consisting of a small vane geared up so as to make many revolutions for one of the pointer pinion.

Oil tubes are provided running from a well in the top of the case to the shaft bearings and to the steel pin which bears on the collar.

Jacquet.—This tachometer, the exterior of which is shown in figure 42, is a hand tachometer of the oblique weight type with a single coiled control spring contained in a slot in the governor shaft. A small steel plunger sliding in a boring in the shaft is connected with the oblique weight by a link passing through a slot in the side of the shaft. Connection with the indicating train is through a ball-and-socket joint in the end of the plunger. The indicating train is of the ordinary sector and pinion type.

The instrument has only a single spindle, although it provides for three ranges of speed. Change of gears is effected by moving the button seen in the neck of the instrument.

FIG. 42.—Jacquet.

Horn.—This is a German double oblique weight type. The governor is similar to that of the Olhovsky and the indicating train the same as in the Jacquet. Likewise it is a single spindle hand instrument.

Standard.—In this tachometer two weights, sliding on pins fixed at right angles to the shaft, fly out when the system is rotated. Their sides each bear against pins on pivoted sectors which mesh with a circular sleeve rack sliding on the governor shaft. As the weights move outward the sectors are rotated and the sleeve raised. A pinion geared to the pointer staff also meshes with the lower part of this circular rack, the motion of which is thus communicated to the pointer.

The governor control is by means of two helical springs, which are put in tension by the rotation of the sector about its pivot.

Loring.—The Loring instrument is a modification of the double oblique weight type. The governor consists of two light weights pivoted outside the shaft in a relatively heavy casting. Rollers on the inner ends of these weights run in slots in the sliding collar, so that as the weights turn the collar is moved. A steel pin driven into the collar slides in the shaft, which is hollow and slotted. On this pin rests a floating hardened steel pin which is raised or lowered with the collar.

Calibration is accomplished by moving the upper collar, adjusting the length of the contact pin arm and bending the control spring.

The scale is graduated uniformly from 500 to 2,500 revolutions per minute in intervals of 20 revolutions per minute and extends over a complete circumference.

The instrument weighs only 14 ounces complete.

FIG. 43.—Waltham air viscosity tachometer.

AIR DRAG OR VISCOSITY TACHOMETERS.

Waltham.—The Waltham tachometer shown in figure 43 is of the air viscosity type described in principle above. There are two concentric cylinders, geared to the main drive, of which the outer one only is shown in the right-hand view. Between them, and separated from them by a thin air film, is placed the inverted cuplike cylinder, mounted in jeweled bearings, to which the pointer is fixed.

The dial is graduated to show speeds from 400 to 2,200 revolutions per minute, the deflection of the pointer for this speed range being about 240 degrees.

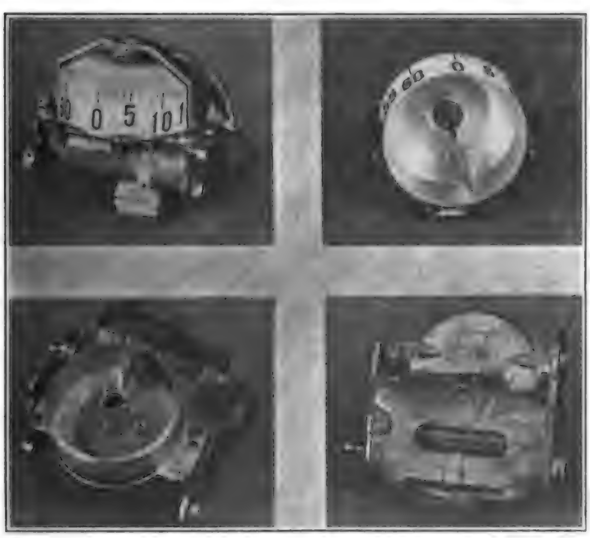


FIG. 44.—Van Sicklen air pump speedometer.

AIR PUMP OR AIR LEAK TACHOMETERS.

Van Sicklen speedometer.—This instrument, shown in figure 44, is typical of the air pump or air leak tachometer mechanism. The lower right-hand view shows the centrifugal air pump and the admission port; the lower left-hand view the discharge orifice and air chamber. Special attention is called to the variable width groove through which the air leaks beneath the vane which is shown with the indicating drum in the upper right-hand view. The width of this orifice is made such that a deflection of the vane is obtained proportional to the driving speed. The upper left-hand view shows the assembled mechanism.

MAGNETO OR ELECTRIC TACHOMETERS.

Tetco.—Figure 45 shows the Tetco electric tachometer. The magneto is of the ordinary bi-polar construction with a single permanent horseshoe magnet. The indicator consists of a suitable range millivolt-meter calibrated to read speeds from 0 to 2,000 revolutions per minute in intervals of 20 revolutions per minute.

MAGNETIC TACHOMETERS.

Warner.—Figure 46 shows a cartridge type of magnetic instrument. The permanent magnet, running in ball bearings, is in the form of a split ring. The drum, in which currents are induced, is held a definite distance from the top of the magnet. The leakage field of the magnet is utilized; consequently the magnet is comparatively strong for a given torque on the disk.

A device for compensating for the effect of temperature consists of an iron ring mounted on three bimetallic levers. Changes in temperature cause this ring to move nearer or away from the magnet, thus distorting the magnetic field and changing, by a suitable amount, the strength of the field utilized for torque.

FIG. 45.—Tetco electric tachometer.

FIG. 46.—Warner magnetic tachometer, cartridge type.

FIG. 47.—Warner magnetic tachometer, airplane type.

The instrument is calibrated by moving the magnet nearer to or away from the indicating disk.

The scale, which is on the side of the drum, is graduated from 0 to 2,000 revolutions per minute in intervals of 25 revolutions per minute.

Figure 47 shows an airplane model of the same instrument. The magnet is geared to the main drive. A disk with pointer attached is used instead of a drum.

The same type of temperature compensator is used as in the cartridge model. It is not shown in the figure.

Attention is called to the pointer damping device which consists merely of a permanent magnet placed near and over the edge of the indicating disk.

The scale extends from 0 to 2,600 revolutions per minute in intervals of 50 revolutions per minute.

Deuta.—Figure 48 shows a cartridge type of German make. The permanent magnet, running in ball bearings, is in the form of a split ring. The inverted drum, in which currents are induced, is mounted in jeweled bearings coaxially with the magnet. Calibration is effected by adjusting the position of a truncated cylinder and thus varying the strength of the magnetic field.

The instrument has no temperature compensator.

The scale extends from 0 to 1,600 revolutions per minute over about 300° and is nonluminous.

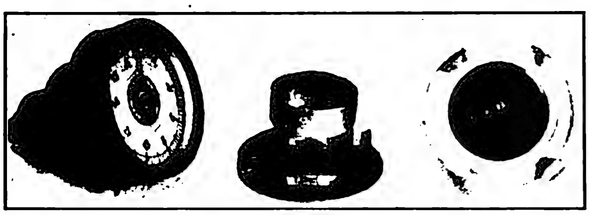


FIG. 48.—Deuta magnetic tachometer.

FIG. 49.—Atmo mercury viscosity tachometer.

MERCURY VISCOSITY TACHOMETERS.

Atmo.—This tachometer, shown in figure 49, is a French instrument of the mercury viscosity type. Mercury contained in a steel cylinder is rotated and tends to drag with it a disk fixed to the pointer staff and mounted concentrically with the cylinder. The deflection of the pointer is controlled by two flat coiled springs, one of which comes into action later than the other, thus tending to make the scale more nearly linear than if only one spring were used. The tachometer dial reads from 400 to 1,600 revolutions per minute, and is nonluminous. The weight of the instrument is approximately 3 pounds.

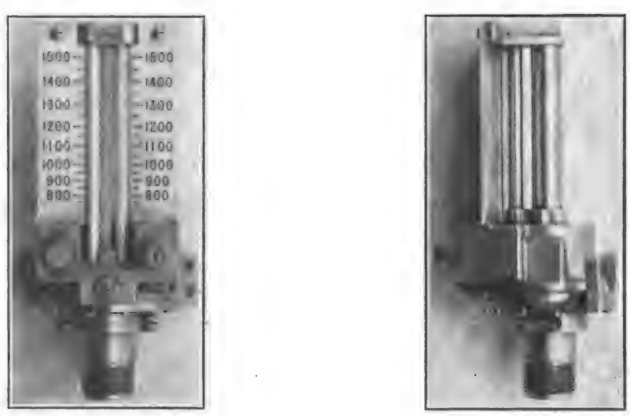


FIG. 50.—Veeder liquid centrifugal tachometer.

LIQUID CENTRIFUGAL TACHOMETERS.

Veeder.—This tachometer, shown in figure 50, is an American instrument of the liquid centrifugal type adapted for airplane use. A paddle wheel rotates in a liquid and forces it through a throttle valve up a system of glass tubes. The height of the liquid indicates the speed. The scale extends from 750 to 1,500 revolutions per minute. The weight of the instrument is approximately $1\frac{3}{4}$ pounds.

REPORT No. 129.

POWER PLANT INSTRUMENTS.

PART II.

TESTING OF AIRPLANE TACHOMETERS.

By R. C. Sylvander.

SUMMARY.

This part describes in detail the apparatus and methods of testing airplane tachometers at the United States Bureau of Standards. Also, the average results of tests on many instruments of the chronometric, centrifugal, magnetic, and air viscosity type are given and are discussed.

INTRODUCTION.

The principal tests made on airplane tachometers are for calibration error, lag, effect of reversing the direction of rotation of the drive shaft, and the effect of various conditions encountered in airplane flights, such as change of temperature, vibration, continued running, tilting, and reduced air pressure. The usual method of determining the error or effect is to compare the reading of the tachometer with that of a master instrument driven from the same shaft. In the following the apparatus and methods for the various tests, as well as the procedure in calibrating the master tachometer itself, are described.

DESCRIPTION OF TESTING APPARATUS.

DRIVING APPARATUS.

The driving apparatus, shown in figure 1, consists of a one-fourth horsepower, direct-current shunt motor (M) and a 14-inch flywheel (O) mounted on a base plate. (M) and (O) run in separate bearings, but the Oldham connection (U) makes perfect alignment between them unnecessary.

Variation in speed is obtained by means of the rheostat (R), which can be connected in series with either the armature or the field of the motor by means of the switch (A). By removing the resistance from the armature circuit and then, after reversing the switch, inserting it in the field circuit, a gradual increase in speed is obtained from zero to 3,000 revolutions per minute. In lowering the speed the operations are reversed.

By this method of varying the speed, power is wasted in heating and the rotation tends to be unsteady at high and low speeds. The latter objection is practically overcome by the flywheel, which, at the same time, allows the speed to be varied with sufficient rapidity from point to point. The method has the advantage that the drive is direct without possibility of slippage.

Fine speed regulation is obtained by friction of the hand on the rim of the flywheel, using the master tachometer (T), figure 1, as an indicator. Special tests have shown that, with proper precautions, the speed may thus be held constant within a few revolutions per minute for tests either on instruments or on the master itself.

MULTIPLE CONNECTION STANDS.

Four forms of multiple drive for connecting instruments to the driving apparatus are used. The connections are designed from the standard instrument, flexible shaft, and engine connections used on American airplanes during the war and shown in sketch No. 75 issued October 11, 1917, by the United States Signal Corps.

The first of these (V) (fig. 2) consists of a series of five right-angle joints connected in series and fitted with vertical extensions of one-fourth inch extra-heavy pipe, approximately 6 inches and 1 foot long, to which the instruments are attached in staggered arrangement by means of standard couplings. The pipe extensions serve both as casings for the flexible cables by which the instruments are driven from the right-angle joints and as rigid supports for the instruments themselves. This form of multiple connection gives good results with centrifugal tachometers, which are frequently unsteady with a rigid drive.

The unit is attached either directly to the shaft of the flywheel by means of an Oldham coupling, as in figure 2, or to one of the sockets of the double drive (X) (fig. 1), either by an Oldham coupling or a flexible shaft, as the stand (Y), figure 1.

(W) (fig. 2) is a form of multiple drive, very similar to (V) (fig. 2). The right-angle joints in this case are the same as those of (V) except that they are made with the standard engine

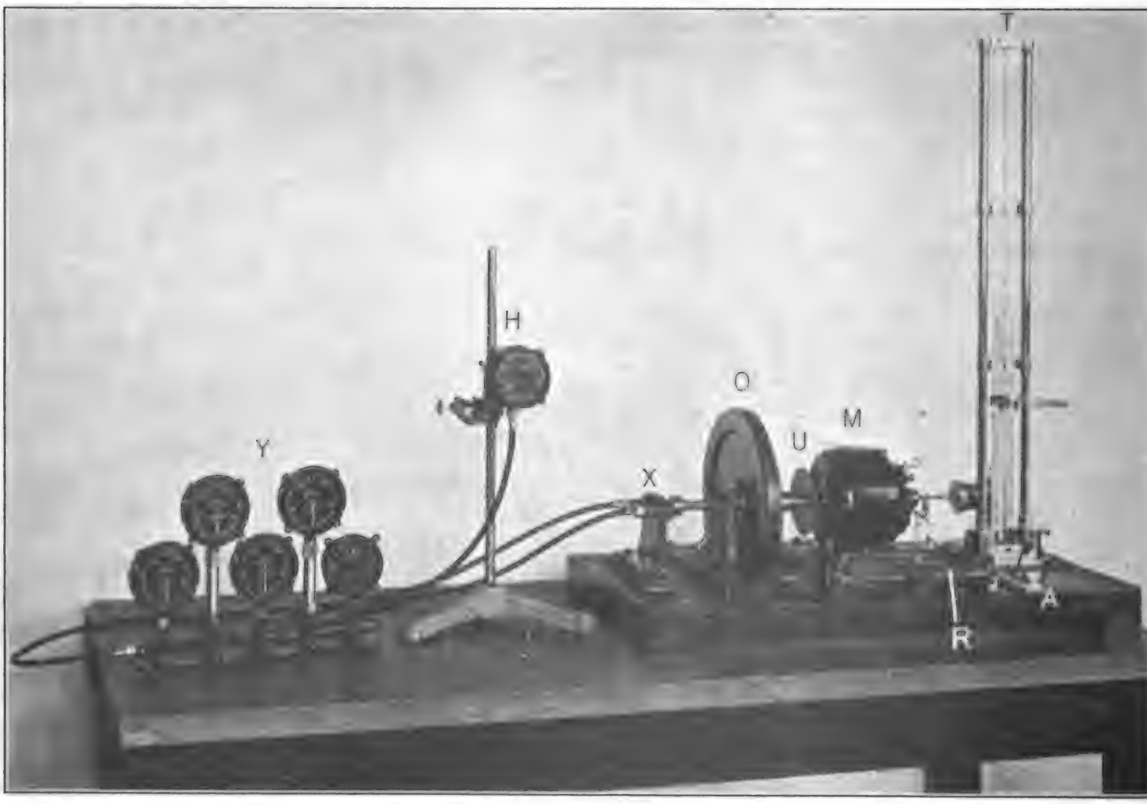


FIG. 1.—Testing apparatus for airplane tachometers.

camshaft connection, so that instruments can be driven from them by means of the regular flexible shaft. This also works well with centrifugals, but requires a separate support for the instruments.

A two-way drive of this kind is (X), shown in figure 1, attached to the driving apparatus. This is used to drive instruments individually, as (H), figure 1, or one or two of the five-way stands, as (Y), figure 1.

(Y) is a rigid multiple drive. The right-angle joints are the same as those of (V), but the instruments are connected rigidly to them—three directly, the other two by means of rods contained in pipe extensions to which the instruments are attached. The right-angle joints are provided, on the ends from which the instruments are driven, with universal tips, giving lateral play, the same as in the regular flexible shaft. Nevertheless this form of drive is apt to cause unsteadiness in the case of centrifugal tachometers, especially in the case of the instruments farthest from the driving end.

MASTER TACHOMETER.

The master tachometer (T), figure 1, is connected to the motor shaft by a rigid drive, so that its running speed is equal to that of the instruments. A comparison of the readings of the two, corrected for the errors of the master itself, thus gives the errors of the instruments.

The master tachometer used at present is a 36-inch Veeder, Form H-4, liquid centrifugal tachometer. This instrument contains colored kerosene and has a paddle wheel in the base which, as it rotates, drives the liquid up in a vertical glass tube. The speed is determined by the position of the meniscus on a scale graduated in revolutions per minute.

The instrument has a very open scale, is direct reading, sensitive, and quick in operation. Investigations made thus far indicate that the secular changes and the errors due to lag, tem-

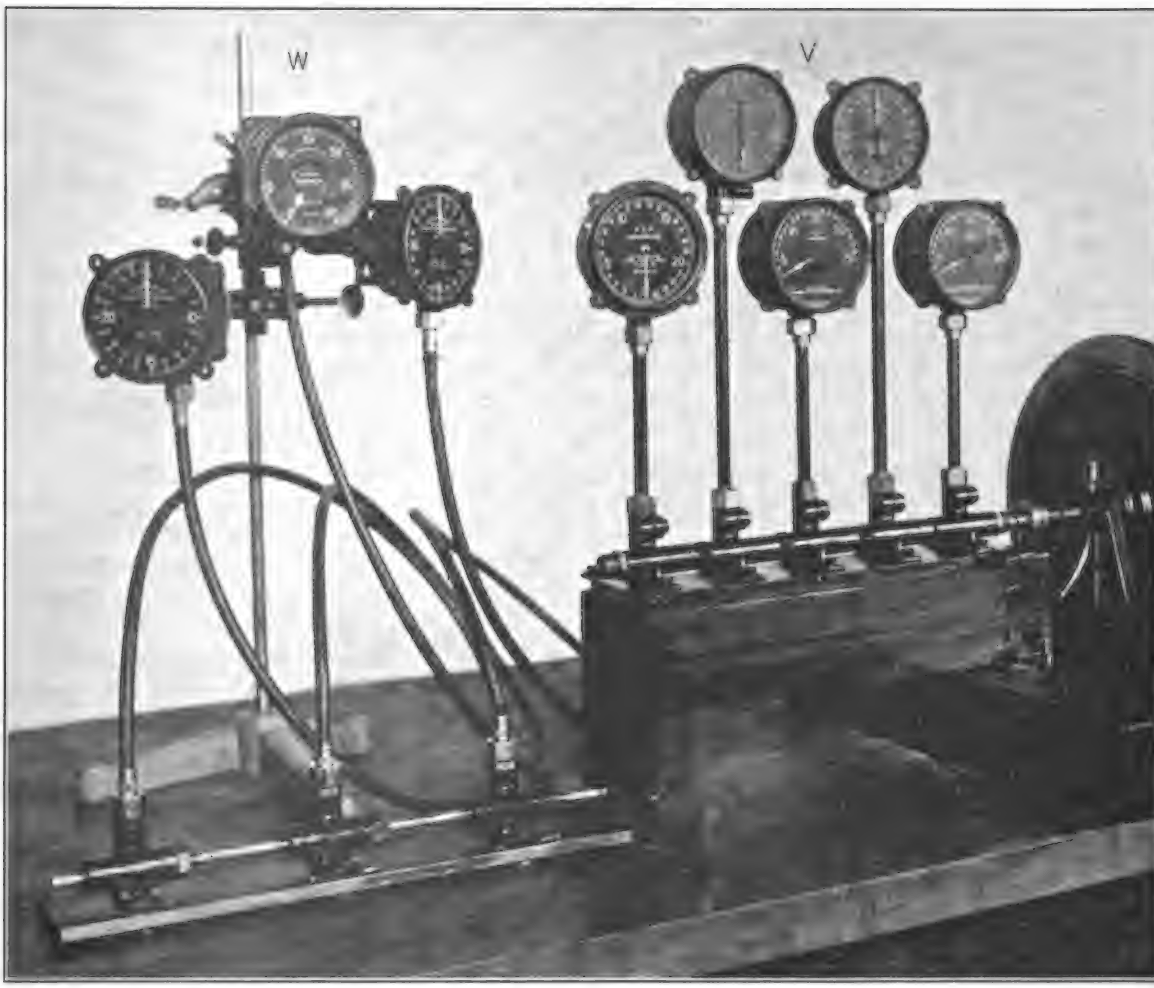


FIG. 2.—Multiple connection stands.

perature, leakage, and inaccuracy in the setting of the zero, though not negligible, are of no serious consequence in the testing of airplane tachometers, which are read ordinarily to five revolutions per minute only.

OTHER APPARATUS.

Another method of testing tachometers is by means of a Tinsley stroboscopic apparatus. A so-called observation disk, on which are certain regular geometric designs, is rotated at the same speed as the tachometer and is illuminated 50 times a second by the instantaneous action of a Neon tube. The lighting of this tube is effected by means of a tuning fork which, as it vibrates, makes and breaks the primary circuit of an induction coil in series with a 2-volt battery. The secondary of the induction coil then gives a discharge through the Neon tube.

It is seen that when the rate of illumination of the tube synchronizes with the sides of any figure on the rotating observation disk that figure will appear to be stationary. If the figure appears to slowly rotate backward, the rotating machine is slow of the tuning fork, and fast when it appears to rotate forward, being exactly at the initial speed when the figure is stationary. Standard speeds are easily picked out by reference to a table.

TESTING METHODS.

DETERMINATION OF CALIBRATION ERROR.

The procedure in determining the calibration error differs somewhat, according to the presence or absence of lag and whether the tachometer is continuously recording, like the centrifugals, or discontinuous in its action, like the chronometrics.

By lag is meant the failure of a tachometer to respond immediately to changes in speed, so that readings taken during or after an increase in the speed are too low; those taken at the time of or subsequent to a decrease in speed too high.

WHEN LAG IS ABSENT.

If lag is known to be absent or negligible, as in the Van Sicklen chronometric and most electric tachometers, the calibration error is determined as follows: One observer holds the reading of the master constant at the speed at which the error is desired. Another observer simultaneously takes a number of readings of the tachometer. The average of these readings minus the fixed reading of the master, the latter corrected for its own error, gives the error of the instrument in revolutions per minute. If the tachometer is a chronometric, it is well to have the readings cover several counting periods, the latter being usually one or two seconds in length. In this way the effect of the fluctuations, which occur under certain conditions even at constant speed in this type of instrument, may be partially eliminated.

WHEN LAG IS PRESENT.

If the instrument has lag, failure to take account of the same may lead to serious inaccuracy. This is because the lag lasts sometimes several minutes after a variation in speed, even when the instrument is tapped or vibrated, so that the observed error is not the true calibration error but the resultant of it and the lag.

In this case the errors with increasing and decreasing speed are observed and their algebraic mean taken as the true calibration error. Thus the effect of the lag, not only of the tachometer but of the master instrument as well, is eliminated. The procedure varies somewhat, according to the type of instrument.

If the tachometer is of the discontinuously recording chronometric type, like the TEL, in which case the lag is caused by lost motion alone, the speed is brought slowly up to, but not beyond, the point at which the error is to be determined and the error noted. The speed is then lowered 50 to 100 revolutions per minute, brought up again, and another reading taken. A few readings are made in this way and an equal number in the same manner, except that the point in question is approached from a higher instead of a lower speed. The algebraic average of these errors is the calibration error of the instrument. The procedure is similar to that employed in the case of screws and other apparatus subject to lost motion.

On the other hand, if the tachometer is of the continuously indicating type, such as the centrifugals, air viscosity tachometers, and magnetics, the speed is raised continuously from the lowest to the highest point of the scale and then lowered again continuously at the rate of about 50 revolutions per minute in 10 seconds. The throttle of the Veeder is kept open in this test by about five turns of the throttling screw, to minimize the lag in the master itself. One observer varies the speed and watches the master, signaling quickly, as the meniscus passes the respective points on the scale, to another observer, who records the error of the tachometer.

Usually a check run is made. In any case an equal number of readings with increasing and decreasing speed are taken at each point. The errors with increasing speed, or "up errors," are recorded in a column opposite the corresponding speed and the errors with decreasing speed,

or "down errors," in a parallel column. With a view to the later calculation of the lag, the up errors at each point are averaged by themselves, and likewise the down errors. The algebraic mean of the two averages gives the calibration error at the point. The values are tabulated in a third column parallel with the columns of up and down errors.

LAG.

The lag is measured numerically by the algebraic excess of the down over the up error or reading. It depends frequently on the rate of variation of the speed and on other conditions, such as vibration, and, in liquid tachometers, on the degree of throttling.

In all measurements of lag care should be taken that the lag of the master tachometer itself is negligible; otherwise the observed values will be too low. The use as a master of a tachometer of the same type as the one under test or of a type, such as the centrifugal, commonly known to be subject to lag, is especially open to question. The lag of the Veeder instrument, with the precautions as to throttling and rate of variation of speed noted above, is five revolutions per minute or less.

The lag is calculated by taking the algebraic difference of the average of the up and down readings already found. The values are recorded in a fourth column parallel with the three error columns. It is customary to omit the sign.

EFFECT OF REVERSAL.

For use in multiple-engined planes where some motors run clockwise and others counterclockwise it is necessary that the tachometer should read the same for either direction of rotation of its drive shaft. A comparison of the calibrations for both directions of drive gives this effect.

EFFECT OF VIBRATION.

Airplane instruments are always subject to more or less vibration from the engine. This, on the one hand, facilitates the movement of the parts and thus reduces the lag. On the other hand, it tends to cause unsteadiness of the pointer, looseness, and wear. The latter effects will be treated in another paragraph.

To test the effect of vibration on the lag, tachometers are mounted on a special table, as shown in figure 3. The vibration is produced by means of an unbalanced weight (W), fastened to the shaft of a small motor (M), screwed to the under side of the table. The lamps (H) regulate the speed of the motor and hence the frequency of the vibration. The legs of the table are provided with rubber tips and fit into holes in the baseboard to keep them in place. In this test the instruments are usually driven by flexible shafts, as in figure 3.

EFFECT OF TIPPING AND ACCELERATION.

Some types of tachometers, for example, the centrifugal, show an error when inclined to the vertical and also when subjected to linear acceleration, as in banking, climbing, and acrobatic flying. For this reason tests are ordinarily made with the instrument in the normal vertical position.

Tipping and acceleration produce the same effect; namely, a change in the effective force of gravity. For example, tipping an instrument upside down is the same as giving it a downward acceleration equal to twice that of free fall. Therefore the acceleration test is omitted and the tipping error taken as a measure of the acceleration effect.

The tipping error is determined by simply tilting the instrument on a ring stand or pivoted board and comparing the error in the inclined position with that in the vertical position.

EFFECT OF TEMPERATURE.

The changes in temperature which occur in airplane flights affect the reading of some types of tachometers. Determinations of the error from this cause are made by means of the thermally insulated chamber shown in figure 4. The walls of this chamber, including the

door which forms the front side, are composed of 4 inches of cork board faced with wood. Lateral windows, consisting of two sheets of plate glass separated by an air space and covered by doors having 1 inch of cork board, give visual access to the chamber. The tachometers are mounted in front of the windows either on the multiple connection stands previously described or on detachable instrument boards fastened to the wall of the chamber. The rigid or flexible connections with the driving apparatus pass through a hole in the wall or door of the chamber. In the case of the instrument boards the tachometers are held in place simply by pins and wooden buttons to facilitate attachment and removal.

Tests are made in the neighborhood of +40° C. and −10° C., a range of 50° C., or about the maximum encountered in airplane flights. The higher temperature is produced by the

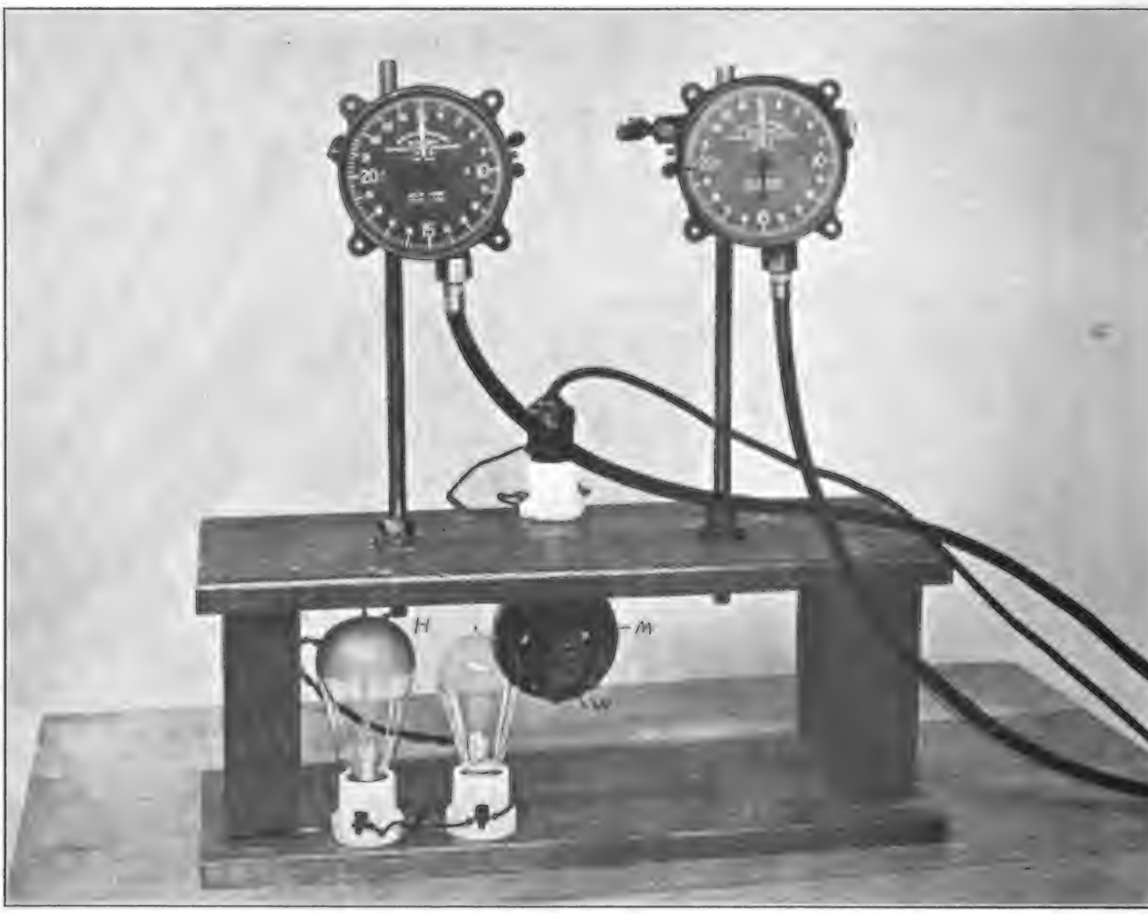


FIG. 3.—Apparatus used in vibration tests.

electric heater shown in figure 4, the lower temperature by brine circulating in the radiator. A fan insures reasonable uniformity of temperature throughout the chamber.

The procedure in determining the error is exactly the same as at room temperature. A comparison of the errors with those at room temperature gives the temperature effect. It is customary to state, for each speed, the maximum effect observed; that is, the greatest difference (algebraic) between the "hot," "cold," and room temperature errors. It is well to note also the effect on the lag, which may be considerable, due possibly to differential expansion or thickening of lubricant.

ENDURANCE AND VIBRATION.

The endurance tests and the test for the effect of long-continued vibration are performed simultaneously, partly to save time, partly to reproduce actual conditions as closely as possible. The apparatus used, shown in figure 5, is contained in a double wooden box to deaden the noise.

The outside of the inner box and the inside of the outer one, as well as the corresponding doors, are completely covered with 1 inch of hair felt, and, in addition, there is an air space of about 1 inch between the boxes on all sides. The outer box is approximately 2 by $2\frac{1}{2}$ by $7\frac{1}{2}$ feet.

The instruments are mounted on multiple connection stands, usually of type (Y), clamped to a table similar to that shown in figure 3 and also having attached to its under side a small eccentrically loaded motor which keeps it and the instruments in constant vibration. Motive power is furnished by one-eighth to one-fourth horsepower motors placed at the ends of the

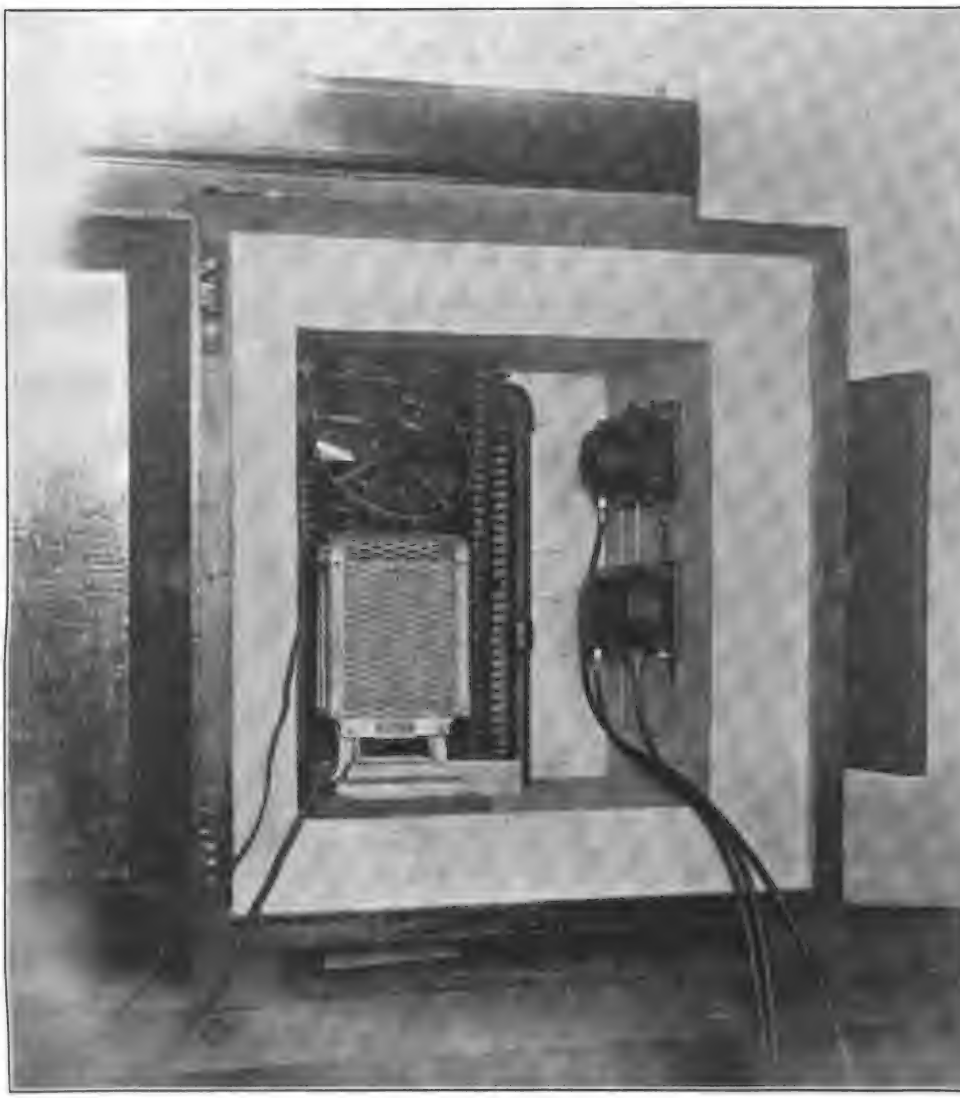


FIG. 4.—Temperature chamber.

table. Connection between the motors and the multiple drives is made though a friction pulley, which allows slippage and thus prevents serious injury to the multiple drive or instruments in case of stoppage; and, also, through a universal joint which gives the flexibility required from the fact that the multiple drive is vibrating, whereas the motor is fixed. An automatic cutout disconnects the motor, in case of stoppage or serious reduction in speed, to prevent burning out of the same, and also stops a clock so as to record the time.

Two different arrangements appear in figure 5. One connected with the left-hand motor, consists of a small horizontal centrifugal governor which collapses as the speed diminishes,

opening a contact gap in the motor circuit and pushing a plunger up against the balance wheel of the clock.

The other, connected by a flexible shaft with one of the multiple drives, is seen in the upper left-hand corner of the chamber. A small fan, driven through the flexible shaft, blows air against a light aluminum wind cup pivoted in horizontal bearings. Above a certain speed the wind cup is held over away from the fan maintaining the connection with the motor (right hand). Below the speed the wind cup, being suitably unbalanced, drops back toward the fan, breaking the motor connection, but making connection between a battery and the electromagnet seen directly back of the right-hand clock. The magnet, being excited, releases a plunger which springs up against the balance wheel of the clock, at the same time again breaking the connection with the battery in order not to exhaust the latter.

Neither of the cut-outs described will function in the case of stoppage of individual instruments, unless accompanied by stoppage or considerable slowing down of the entire apparatus.

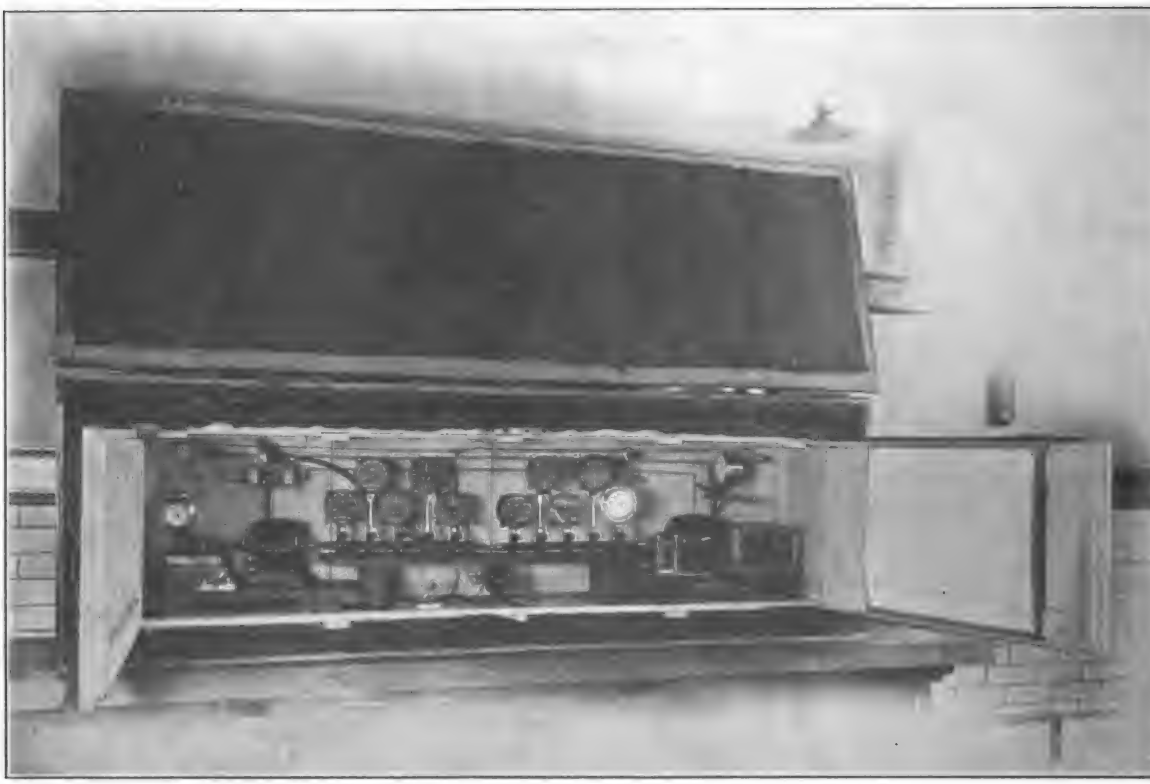


FIG. 5.—Endurance—vibration apparatus.

When this occurs, however, they serve the double purpose of protecting the motor and of recording the time, so that the duration of the run may be known.

The normal length of run is 150 hours. After the run the instruments, which have suffered no breakdown or serious mechanical defect, are recalibrated and the change in calibration at each point as a result of the run tabulated. All instruments are then dismantled and examined for wear, looseness, slippage, lubrication difficulties, or other mechanical troubles.

EFFECT OF REDUCED AIR PRESSURE.

Some tachometers, requiring air for their action, are tested for the effect of the diminution in air pressure above the surface of the earth.

The tachometer is driven inside a partially evacuated chamber through a mercury seal. The use of a packed bearing and the temperature changes, when the driving motor itself is placed within the chamber, are thus avoided. Figure 6 shows the apparatus.

(A), (B), (C), and (D), (fig. 6), are, respectively, the drive motor, master tachometer, mercury seal, and vacuum chamber. The chamber consists of a glass bell jar (E) inverted on a steel plate (F). The plate and jar are held together partly by the weight of the latter and partly after evacuation, by the pressure of the outer air. The joint between them is hermetically sealed by the rubber gasket (K), which is cemented to the edge of the jar with shellac, the surface of the plate beneath being smeared with vaseline. The tachometer (T) is supported on a stand (J) fastened to (F).

The mercury seal (C) is of peculiar construction. It consists of a heavy walled glass manometer tube about 30 inches high. The tube is connected at one end with the air chamber through the packed coupling (G). The other end is open to the air. A standard flexible cable and casing, the latter perforated at several points, are placed in the manometer tube. Connection is made at (H) with the motor shaft, at (L) with the tachometer. The tube is partly filled with mercury. Air is exhausted from (D) through the pump connection (O). As this is done mercury rises in one arm of (C) and falls in the other, as in an ordinary manometer, until the difference in pressure in the chamber and the outer air is counterbalanced. Mercury at the same time runs in around the cable through the perforations in the casing, forming an air-tight seal about the cable without sensibly impeding its rotation. A thermometer (M) and an aneroid barometer (N) show, respectively, the temperature and pressure in the chamber.

A comparison is made of the calibration error at low pressures with that at normal atmospheric pressure. This may be determined at different speeds for the same pressure or for different pressures at the same speed. Or the pressure effect may be observed directly by holding the speed constant and either exhausting or readmitting the air to the chamber and noticing the change in reading.

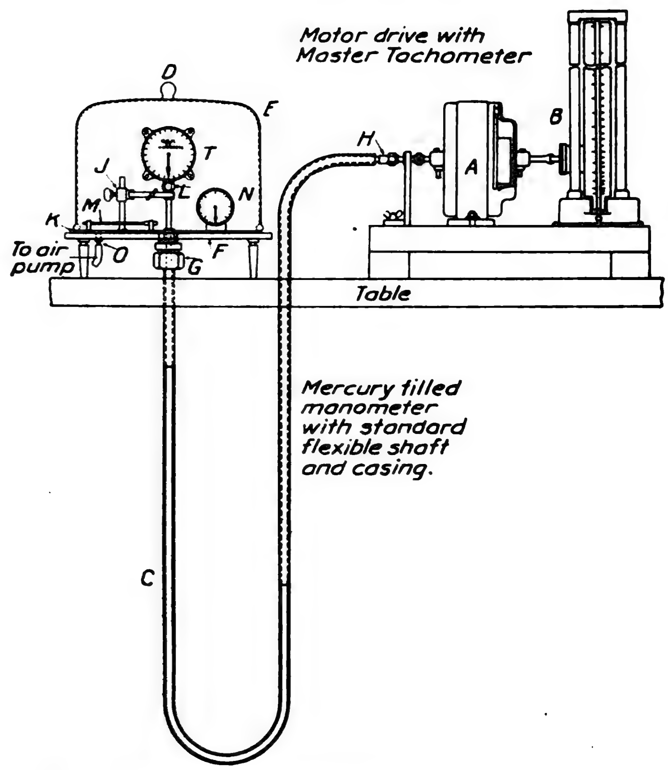


FIG. 6.—Apparatus for testing tachometers under reduced pressure.

The apparatus has been used at speeds up to 2,500 revolutions per minute and at pressures as low as one-half atmosphere, corresponding to an altitude of 20,000 feet.

CALIBRATION OF MASTER TACHOMETER.

Calibration and investigation of the master tachometer itself are done by an absolute method, by which the revolutions and the time are measured directly. Two different appliances are in use, both of the kind in which a revolution counter is operated automatically by means of electric time signals.

The first is a slight modification of an apparatus employed by the Veeder Manufacturing Co., and described by Amasa Trowbridge on pages 1221–1223 of the Transactions of the American Society of Mechanical Engineers for 1908.

It consists, in brief, of a relay, electromagnets, battery, and switches. The time signal current is passed through the relay, which, in turn, operates the electromagnets, and these throw the counter into and out of connection with the shaft whose speed is to be determined.

A possible advantage over some apparatus of this kind consists in the fact that the counter is engaged and disengaged by identical operations. Any error, due to a difference in the lag of the counter behind the time signal on connecting and that on disconecting, is thus avoided. The electromagnets are arranged so as to give directly, without the use of links or pivoted joints, the necessary rectilinear motion for engaging and disengaging the counter.

Figures 7 and 8 show the apparatus. The wiring diagram (fig. 8) shows that the push buttons (P_1) and (P_2) are in series with the contact gap (A) of the relay, the battery (B) and

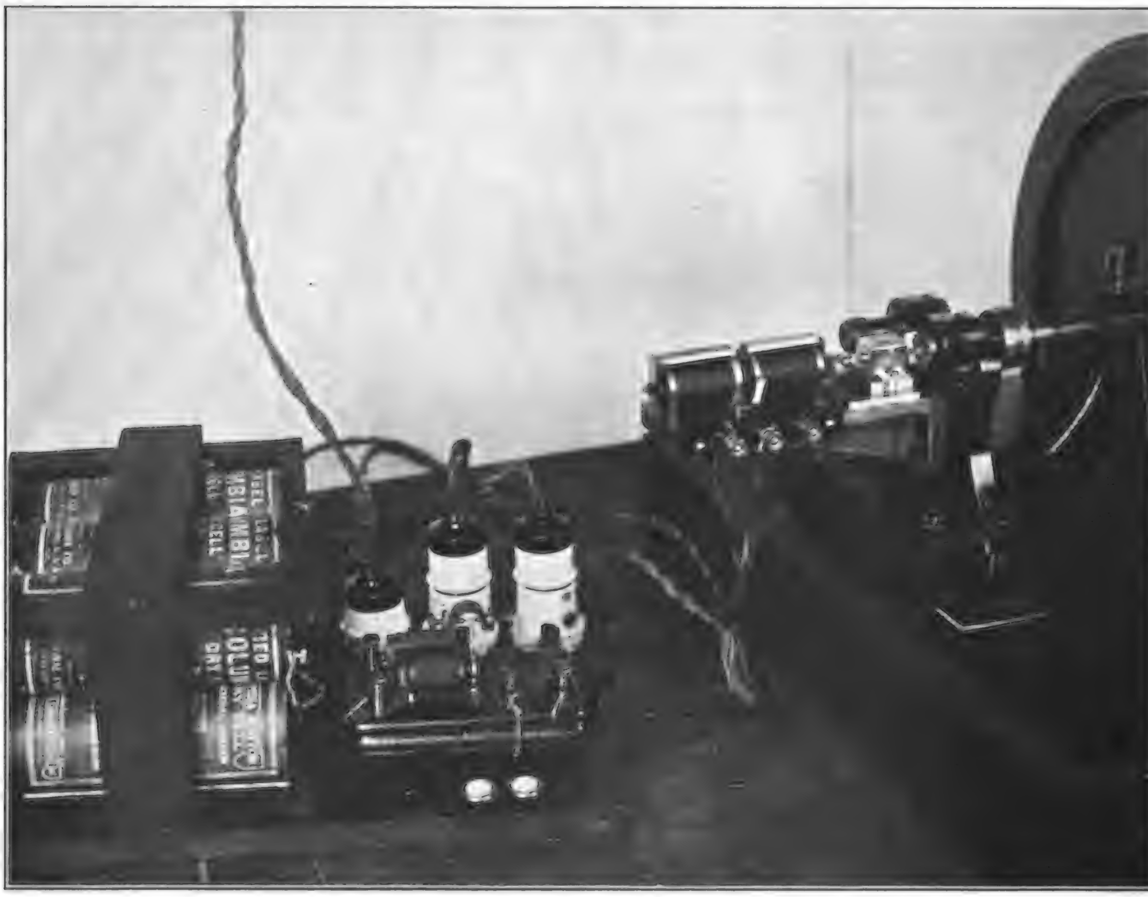


FIG. 7.—Time signal apparatus for calibrating master tachometer.

the electromagnets (M_1) and (M_2), respectively, through the connection sockets (S_1) and (S_2). Therefore, if either of the push buttons is held down, the corresponding electromagnet is actuated by the time signals. Now the magnets and counter (C) are coaxial and, by their attraction of the steel armatures (D_1) and (D_2), move the vane (L) which slides endwise in a slit in the end of the counter spindle and with which the spindle rotates. The movement of (L) is accomplished through the rod (E), which slides in holes in the cores of the magnets and to which (D_1) and (D_2) are fixed, the slip connection (G) and the rod (K), which is free to slide in a hole in the counter spindle and to which (L) is fastened. The end plates (R_1) and (R_2) are of brass. The plates (W_1) and (W_2), however, are of steel, and form, with the cores of the magnets, the return bars (H_1) and (H_2) and the base plate (T), also of steel, the partial magnetic circuits which are completed by (D_1) and (D_2). (Y) is a guiding pin to prevent rotation of (E), (D_1), and (D_2).

According as (M_1) or (M_2) is excited, (L) is thrown into mesh with the rotating clutch (N) on the end of the shaft (F) whose speed is to be determined or with the stationary clutch (O). It is held in either position by residual magnetism. Furthermore, the width of (L) is made slightly less than, but as nearly as possible equal to, the distance between (N) and (O), so that (L) goes into mesh with the one as soon as possible after going out of mesh with the other, but can not be in mesh with both clutches simultaneously.

The above form of revolution counter has the advantage that it may be connected and disconnected without moving the counter as a whole,

Suppose that, to start with, both push buttons (P_1) and (P_2) are up and that (D_2) is against (M_2). (L) is then out of connection with (F) and the counter is at rest. The reading of the counter is taken to a fraction of a revolution corresponding to the number of segments or pockets into which the clutches (N) and (O) are divided. Then just before a given signal the button (P_1) is pushed and held until after the passage of the signal. From the foregoing it follows that at the instant at which the signal is received, (M_1) is actuated, (D_1) is attracted up to (M_1), (L) is thrown into mesh with (N), and the counter begins to record the revolutions of (F). (P_1) is now released. Next, just previous to another stated time signal, preferably an even number of minutes after the first, (P_2) is pressed and held until after the signal occurs. Obviously the effect will now be, at the instant at which the signal arrives, to excite (M_2) attract (D_2) up to (M_2), throw (L) out of mesh with (N), and stop the counter. This stoppage is immediate, "coasting" of the counter being prevented by the mesh of (L) with (O). The counter is then read again. The difference between the initial and final readings gives the revolutions during the interval between the time signals, and hence the speed of (F).

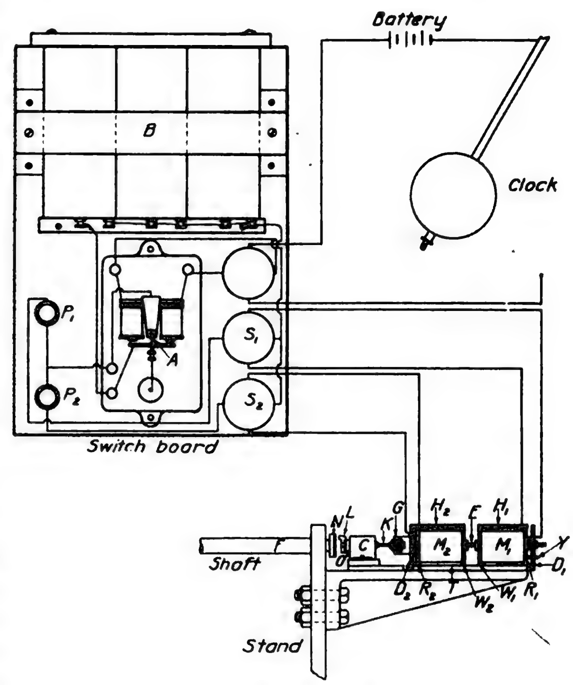


FIG. 8.—Time signal apparatus.

The time signals at the Bureau of Standards occur every second, the minutes being recognized by the omission of the fifty-ninth signal in each minute. The operation of the apparatus and the regulation of the speed are easily performed by a single observer. Further simplification, however, is obtained when the closures of the circuit, as by (P_1) and (P_2), are made automatically at intervals of one or more minutes by a clock-driven commutator. Also it is proposed to construct an apparatus with two counters arranged to operate alternately. The two-second pause may then be utilized without the necessity of waiting over every other minute.

The magnets (M_1) and (M_2) being practically alike, as stated above, the operations of connecting and disconnecting the counter are sensibly identical and the effect of inductive lag is eliminated. Also if (L) meshes to equal depth with the clutches (N) and (O), the errors due to the time required for (L) to free itself from the clutches at the beginning and end counterbalance each other. An error caused by the revolutions lost while (L) is traversing the clearance distance between it and the clutches is, however, present. This error is determined by the amount of clearance and the velocity of (L), the latter depending in turn on the pull of the magnets, the mass of the moving system, and the frictional resistance. Though as yet no separate study of this source of error has been made, the close agreement, within a few revolutions, of the results with those obtained by other methods and elsewhere indicate that the

apparatus is sufficiently accurate for the purpose for which it is intended. The separate readings themselves agree, under the best conditions, to within one-fourth to one-half a revolution.

A second, more complicated, and theoretically less accurate apparatus appears in figure 9. In this apparatus the counter is thrown in and held in by magnetic attraction, but is disengaged by a spring. The operations are timed automatically by electric signals from a clock, the observer having only to press a button twice and throw a switch once.

The counter is mounted on a sliding rod fixed to the armature of an electromagnet, seen at the right of the figure, and is fitted with a star wheel which engages a pin in the end of the shaft whose speed is to be determined. A helical compression spring encircling the sliding rod holds the counter normally out of connection with the shaft.

The arrangement is such that current begins to flow through the electromagnet at the instant of a given time signal, and continues to flow, thus putting the counter into and holding it in connection with the shaft. Another signal, exactly a minute later, breaks the circuit of

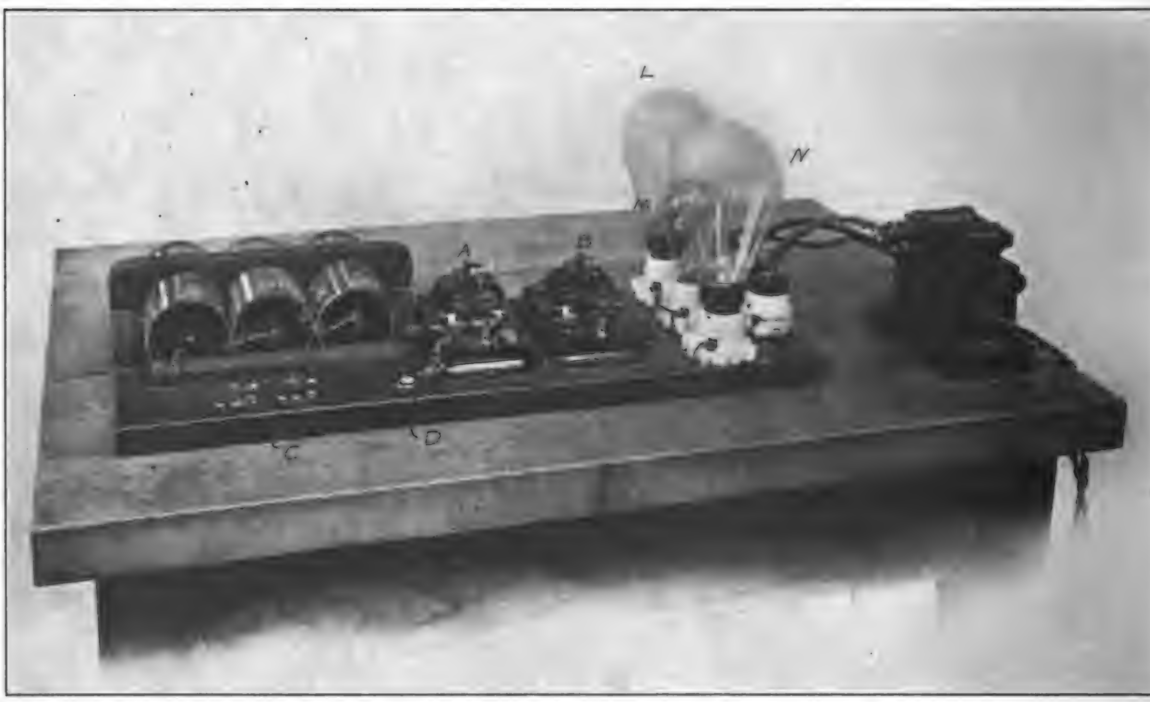


FIG. 9.—Time signal apparatus used in calibrating master tachometer.

the electromagnet and the counter is disconnected. The necessary electrical connections for these operations are made by means of the switchboard seen in the center of figure 9.

Ordinarily only the relay (A) is actuated by the time signal. If the push button (D) is pressed, however, the relay (B) is also operated by the signal. (B) is provided with an insulated stud on the inner side of its armature, connected as shown, and when actuated puts itself and the counter magnet in connection with the 110-volt mains through the lamps (L), (M), and (N) in parallel. At the instant of the first signal occurring after (D) is pressed, therefore, the counter magnet is excited and the counter begins to record revolutions. Moreover, since the exciting of (B) itself maintains the connections, the current continues through the counter magnet. The counter is thus held in connection with the shaft and continues to count revolutions.

The switch (C) is now moved to the left. The contact with the central studs, which is made before that with the right-hand studs is broken, disconnects (B) from the mains but maintains the connection with the counter magnet through the lamps (L) and (M), so that counting still proceeds. The contact with the left-hand buttons merely rearrange the connections so that actuation of (B) will now disconnect the counter magnet from the mains

instead of connecting it as before. Accordingly, (D) being pressed, at the time of the next following signal, the counter magnet is disconnected. The counter is thus disconnected and ceases to record revolutions. The time and the revolutions both being known, the speed is readily calculated.

This apparatus has the relative disadvantages of complexity, comparative uncertainty in action, and, theoretically, of error due to the fact that the counter is connected and disconnected by different means—by magnetic attraction and by spring force, respectively. It is, therefore, not considered, on the whole, as desirable as the first apparatus described.

RESULTS OF TESTS ON AMERICAN AIRPLANE TACHOMETERS.

Detailed results of various tests on several types of American airplane tachometers are given below. A brief summary of these results has already been given in an earlier section of this report.

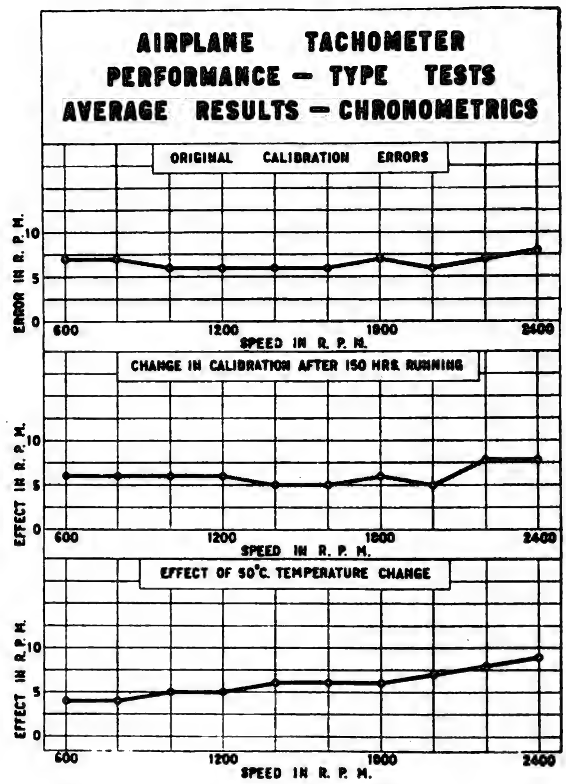


FIG. 10.

The following types were tested thoroughly: Chronometric, centrifugal, and magnetic. Other types, such as air viscosity and electric, were tested less completely but sufficiently to prove that they were not at present well adapted to airplane use. For this reason the second group of instruments were not given certain tests which they could probably pass successfully.

The performance of each of the chronometric, centrifugal, and magnetic types is first discussed separately and then compared with that of the other types.

CHRONOMETRIC TACHOMETERS.

Chronometric tachometers were studied for calibration errors, lag, effect of temperature change, tilting, and running on the calibration. Two makes, based upon the same principle but differing greatly in detail, were tested. In the following discussion these two makes are identified by the letters "A" and "B". A weighted mean of the results for the two makes is tabulated as the performance of the type, and is plotted in figure 10.

Calibration.—The calibration errors of a new instrument of this type are usually small. The average errors of 204 instruments, of which 79 were of make "A" and 125 of make "B," are tabulated below in Table I, together with the average errors of instruments of each make.

TABLE I.

Speed in revolutions per minute.	Average errors in revolutions per minute.		
	Make "A."	Make "B."	Type.
600	9	5	7
800	9	5	7
1,000	8	4	6
1,200	7	5	6
1,400	6	5	6
1,600	6	5	6
1,800	6	7	7
2,000	6	6	6
2,200	7	7	7
2,400	9	7	8

The average error for all speeds was about 7 revolutions per minute for make "A" and 6 revolutions per minute for make "B."

The percentage of instruments having errors between the following limits—namely, greater than 20, 20 to 10, and 10 to 5, respectively—was 11, 69, and 20 for make "A" and 5, 46, and 49 for make "B."

Effect of running on calibration.—Table II shows the effect of 150 hours running and vibration on the calibration for 35 instruments of make "A" and for 51 of make "B" and also for the type.

TABLE II.

Speed in revolutions per minute.	Average effect in revolutions per minute.		
	Make "A."	Make "B."	Type.
600	7	5	6
800	6	6	6
1,000	6	6	6
1,200	7	5	6
1,400	5	5	5
1,600	6	5	5
1,800	6	6	6
2,000	5	5	5
2,200	8	5	7
2,400	8	6	7

It is seen that the average effect in each make is practically that of the type, or 6 revolutions per minute.

Of 35 instruments of make "A" 14 per cent showed maximum changes of 20 revolutions per minute or over, 57 per cent changes between 10 and 20 revolutions per minute, and 29 per cent showed changes less than 10 revolutions per minute.

Of 51 instruments of make "B," 8 per cent showed changes over 20 revolutions per minute, 45 per cent between 10 and 20 revolutions per minute, and 47 per cent less than 10 revolutions per minute.

Temperature.—The average effect of 50° C. change in temperature is tabulated below in Table III for 36 instruments of make "A" and 34 of make "B" and for the type.

TABLE III.

Speed in revolutions per minute.	Average effect in revolutions per minute.		
	Make "A."	Make "B."	Type.
600	7	0	4
800	8	0	4
1,000	9	1	5
1,200	9	1	5
1,400	10	2	6
1,600	11	1	6
1,800	11	1	6
2,000	13	2	7
2,200	13	2	8
2,400	15	3	9

It is seen that the effect is greater for instruments of make "A" than for those of make "B." The average effect for the type is small, the maximum being 9 revolutions per minute. It will be noticed that the temperature effect increases slightly with the speed.

Of a group of 36 instruments of make "A" tested for the effect of temperature change 14 per cent had effects equal to or greater than 25 revolutions per minute, 70 per cent between 15 and 25 revolutions per minute, and 16 per cent less than 15 revolutions per minute. Of 34 instruments of make "B" only one instrument showed an effect at any point of 25 revolutions per minute, the remaining 97 per cent having the maximum effect less than this amount.

Tilting.—Instruments of the chronometric type read the same for all positions of the axis with respect to the vertical.

Lag.—The chronometric tachometer has no lag due to friction and inertia such as is found in the centrifugal. A time lag is, however, characteristic, owing to the fact that the pointer is locked in position during each counting period. Consequently, any change in speed during this period, usually one second, will not be shown until its end, and may be considerable. But, if the speed is increased to a given value and held constant for a few seconds, the reading will be practically the same as if the speed had been decreased to the same value and held there.

A pointer-steadying device used in instruments of the type denoted make "A," causes a difference between up and down readings of 20 revolutions per minute or more, due to lost motion. This lost motion is purposely inserted, a steady pointer evidently being deemed by the manufacturers as more desirable than freedom from lag.

If chronometric tachometers do not have this special pointer-steadying device sudden slight jumps of the pointer are usually present. This is due to the fact that the teeth of the fine-toothed pinion do not always mesh correctly with those of the rack or counter gear, and slippage or sliding of one tooth upon its mate until proper mesh is made must occur before the mechanism functions properly. The maximum jump which could occur from this cause is in the neighborhood of 15 revolutions per minute. The jump observed in practice is usually less than 5 revolutions per minute.

Durability.—An idea of the durability of the chronometric tachometer is given by the following data: Of 50 instruments of make "A" tested for endurance 14, or about 28 per cent, failed before the test was completed. Of 69 instruments of make "B," 14 or 20 per cent failed. The length of the test was 150 hours.

It is only fair to say, however, that of the failures of make "B" the larger number occurred in instruments of the earlier production. The later instruments were improved so that of the latter third of the instruments submitted to the tests the failures were few.

Conclusions.—It is seen that the performance of the chronometric type is very good as regards accuracy under different conditions of temperature, altitude, etc. Owing to the fact, however, that the readings are intermittent, it is not so satisfactory as an indicator for speeds which are changing. For instead of indicating the change in speed gradually as it occurs, it

shows all at once at the end of a given time interval the total change in speed which occurred during that interval. This lack of sensitivity is a serious defect for certain kinds of work and certainly is not a desirable feature for use in airplanes.

CENTRIFUGAL TACHOMETERS.

Centrifugal tachometers were studied for calibration errors, effect of running, tilting, lag, effect of temperature change and durability. Two makes, "C" and "D," both of the so-called governor type, were tested. The results of these tests are given below for instruments of each make, and a weighted mean of these results is tabulated as the average error for the type, and is plotted in figure 11.

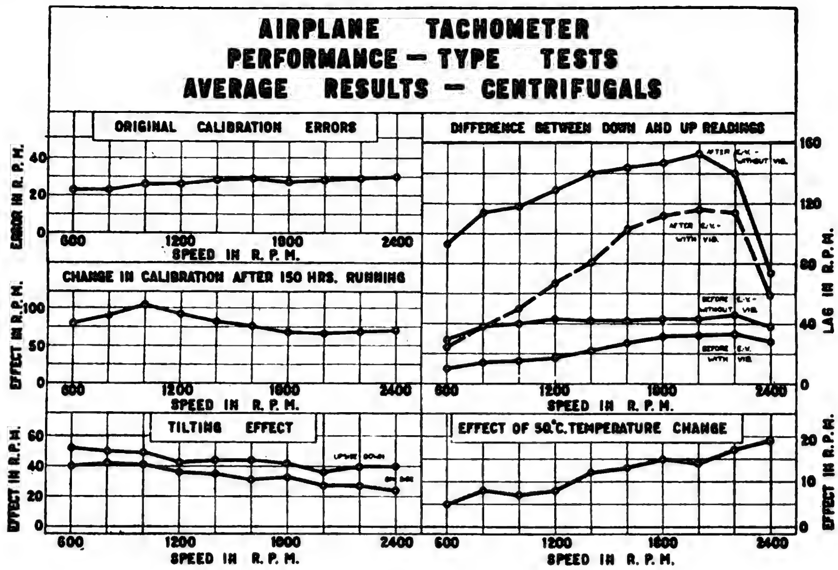


FIG. 11.

Calibration.—The average calibration errors of new instruments of the centrifugal type are somewhat higher than those of the chronometric type. The average errors of 73 instruments, of which 9 were of make "C" and 64 of make "D," are tabulated below, together with the average errors of each make.

TABLE IV.

Speed in revolutions per minute.	Average error in revolutions per minute.		
	Make "C."	Make "D."	Type.
600	24	23	23
800	20	25	23
1,000	20	31	26
1,200	23	31	26
1,400	25	30	28
1,600	28	29	29
1,800	27	28	27
2,000	27	28	28
2,200	30	28	29
2,400	31	29	30

The average error for all speeds was 26 revolutions per minute for make "C," 28 revolutions per minute for make "D," and 27 revolutions per minute for the type. Of make "C," 89 per cent had errors at some point of 20 revolutions per minute or more and of make "D," 71 per cent.

Effect of running on the calibration.—The average effect of 150 hours running and vibration on the calibration is shown below for 33 instruments of which 5 were of make "C" and 28 of make "D."

TABLE V.

Speed in revolutions per minute.	Average effect in revolutions per minute.		
	Make "C."	Make "D."	Type.
600	26	96	86
800	24	90	81
1,000	20	104	92
1,200	22	92	82
1,400	20	82	73
1,600	20	75	67
1,800	16	68	61
2,000	12	66	58
2,200	17	69	62
2,400	27	70	64

The average change in calibration caused by running is 20 revolutions per minute for make "C" and 81 revolutions per minute for make "D." The average effect for the type is 73 revolutions per minute.

Of make "C," the greatest effect observed at any point was 58 revolutions per minute; 80 per cent of the instruments tested showed an effect at one or more points of over 20 revolutions per minute.

Of make "D," 65 per cent had errors at some point of 50 revolutions per minute or more, 15 per cent between 50 and 20 revolutions per minute, and 20 per cent less than 20 revolutions per minute.

Tilting.—Table VI shows the effect of the position of the instrument with respect to the vertical. The error for each point was determined with the instrument (1) upside down and (2) on its side. In all cases the reading in these positions was higher than in the vertical position.

TABLE VI.

Speed in revolutions per minute.	Average change in reading due to tilting in revolutions per minute.					
	Upside down.			On side.		
	Make "C."	Make "D."	Type.	Make "C."	Make "D."	Type.
600	30	63	52	15	53	40
800	35	57	50	25	50	42
1,000	38	55	49	23	50	41
1,200	28	51	43	25	41	36
1,400	25	53	44	25	40	35
1,600	22	56	44	14	39	31
1,800	15	56	42	13	44	33
2,000	13	47	36	6	38	27
2,200	13	54	40	6	38	27
2,400	15	53	40	10	31	24

The average errors for make "C" are 23 and 16 revolutions per minute for the upside down and on side positions, respectively. For make "D" the corresponding average errors are 55 and 42 revolutions per minute.

Lag.—The differences between readings taken with decreasing speed and with increasing speed are tabulated below. Four tables are given showing the lag (1) before the endurance-vibration run without vibration, (2) the same with the instrument being vibrated while calibrated, (3) after the endurance-vibration run without vibration, and (4) after the endurance-vibration run with vibration. These values are shown graphically in the upper right-hand plot of figure 11. The effects of vibrating the instrument during the calibrations before and after the endurance run are evident from the data and plots; also the effect of the run itself.

TABLE VII.

Speed in revolutions per minute.	Average lag in revolutions per minute.											
	Before endurance-vibration run.						After endurance-vibration run.					
	(1) Without vibration.			(2) With vibration.			(3) Without vibration.			(4) With vibration.		
	Make "C."	Make "D."	Type.	Make "C."	Make "D."	Type.	Make "C."	Make "D."	Type.	Make "C."	Make "D."	Type.
600	2	36	29	4	13	10	27	129	93	10	29	24
800	9	46	38	6	20	14	35	158	114	18	44	38
1,000	11	48	40	7	20	15	40	162	118	16	61	50
1,200	15	50	43	8	23	17	41	178	129	25	81	67
1,400	14	49	42	10	29	22	42	195	140	22	100	81
1,600	19	48	42	12	36	27	41	201	144	27	128	103
1,800	20	49	43	14	42	31	45	204	147	31	139	112
2,000	22	49	43	16	43	32	50	211	153	27	146	116
2,200	25	52	46	13	46	33	54	187	140	30	142	114
2,400	23	42	38	15	36	28	39	93	74	29	69	59
Number of instruments tested	9	34	43	9	13	22	5	8	13	2	6	8

For make "C" the average lag before the endurance-vibration run is 16 revolutions per minute without vibration, and 11 revolutions per minute when vibrated. The corresponding values after the endurance run are 41 revolutions per minute and 23 revolutions per minute respectively. The lag was increased by from 100 to 150 per cent as a result of the 150 hours run.

For make "D" the average lag before the endurance-vibration run is 47 revolutions per minute without vibration and 29 revolutions per minute when vibrated. The corresponding values after the endurance run are 172 revolutions per minute and 94 revolutions per minute. For this make the effect of running was to increase the lag by from 200 to 250 per cent.

The averages for the type are (1) 40 revolutions per minute before the run and without vibration, (2) 23 revolutions per minute with vibration, (3) 125 revolutions per minute after the run without vibration, and (4) 76 revolutions per minute with vibration. The average effect of vibration during the calibration is to reduce the lag by about 40 per cent; the average effect of the endurance run is to increase the lag by over 200 per cent.

Temperature.—The average effect of 50° C. change in temperature is tabulated below for 3 instruments of make "C" and 11 of make "D" and for the type.

TABLE VIII.

Speed in revolutions per minute.	Average effect in revolutions per minute.		
	Make "C."	Make "D."	Type.
600	1	9	5
800	5	10	8
1,000	6	8	7
1,200	5	10	8
1,400	8	16	12
1,600	7	19	13
1,800	11	18	15
2,000	9	19	14
2,200	10	24	17
2,400	11	26	19

The average effect for make "C" is 7 revolutions per minute, for make "D" 16 revolutions per minute, and for the type 12 revolutions per minute.

Durability.—The centrifugal tachometer is not likely to break down until badly worn. A few instances of the pointer being loosened on its staff were, however, noticed and in one or two instruments defective steel balls in the end bearings caused an unsteady pointer. In all other cases the instruments continued to indicate, although in many cases the reading was in error by several hundred revolutions.

Conclusions.—It is seen that the average performance of instruments of make "C," although poor, is much better in most respects than that of instruments of make "D." This is explained

in part by details of design, make "C" having a light, high speed governor while make "D" has a heavy and comparatively slow speed governor. Most of the difference, however, is due to superior quality of workmanship and finish of critical parts found in make "C."

The average performance of the centrifugal type tachometer is far from satisfactory especially in regard to lag and change of calibration with use. The average errors or effects for all speeds are as follows: Calibration error, 2 per cent; effect of 150 hours running on calibration, 5 per cent; original lag, 3 per cent without vibration and 2 per cent with, and after 150 hours' running 9 per cent without vibration and 5 per cent with; effect of 50° C. temperature change, 1 per cent; effect of tilting, 4 per cent for the "inverted" position and 3 per cent for the "on side" position.

MAGNETIC TACHOMETERS.

Magnetic tachometers were studied for calibration errors, effect of running and vibration, tilting, lag, effect of temperature change, and durability. All instruments tested were of the same make and design. The results are shown graphically in figure 12.

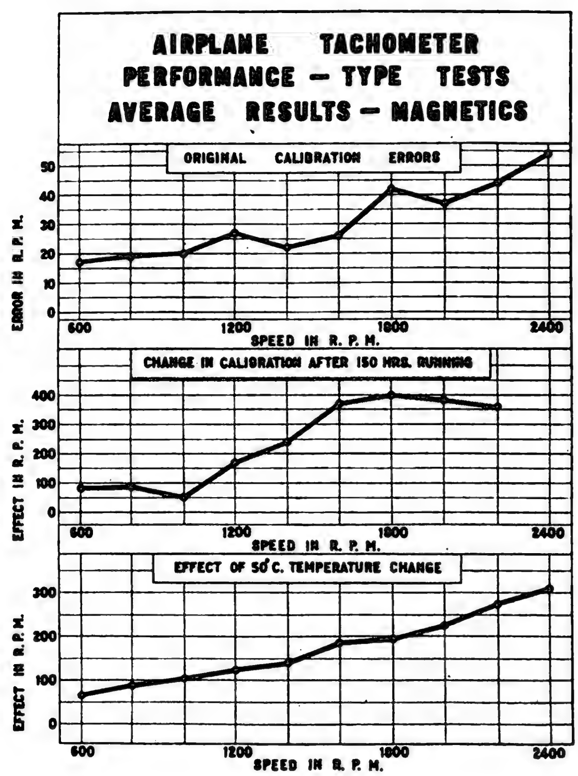


Fig. 12.

Calibration.—The average calibration errors of six magnetic tachometers are tabulated below.

TABLE IX.

Speed in revolutions per minute.	Average error in revolutions per minute.
600	17
800	19
1,000	20
1,200	27
1,400	22
1,600	26
1,800	42
2,000	37
2,200	44
2,400	54

The average error for all speeds is 31 revolutions per minute.

No instrument had all errors less than 20 revolutions per minute; 60 per cent had some error over 50 revolutions per minute, one instrument having errors as high as 375 revolutions per minute. The errors of this instrument are not included in the data tabulated above, as they were considered anomalous.

Effect of running on calibration.—The effect of running and vibrating for 150 hours on the calibration of one airplane model magnetic tachometer is shown in the table below.

TABLE X.

Speed in revolutions per minute.	Average effect in revolutions per minute.
600	81
800	88
1,000	50
1,200	170
1,400	239
1,600	367
1,800	400
2,000	381
2,200	360

The average effect is 237 revolutions per minute; the maximum effect is 400 revolutions per minute at a speed of 1,800, or an error of about 22 per cent.

This is considered very poor performance.

Tilting.—The magnetic tachometer reads practically the same for all positions of its axis.

Lag.—The lag in the magnetic tachometer rarely exceeded 20 revolutions per minute. If the speed were held constant after being either decreased or increased the reading would be the same after a second or two, the lag being caused wholly by sluggishness of action.

Temperature.—The average effect of about 50° C. change in temperature is tabulated below for five instruments.

TABLE XI.

Speed in revolutions per minute.	Average effect in revolutions per minute.
600	64
800	86
1,000	103
1,200	122
1,400	139
1,600	184
1,800	194
2,000	223
2,200	273
2,400	308

In general the effect of lowering the temperature is to increase the reading for a given speed, that of raising the temperature to decrease it.

The average effect is 170 revolutions per minute. The maximum effect is 308 revolutions per minute at a speed of 2,400, or about 13 per cent.

Durability.—The magnetic tachometers tested for endurance all showed some serious defect as a result of the run. The usual and most serious was a pitting of the lower jewelled bearing in which the electrically conducting drum or disc was mounted. This allowed it to move into a stronger magnetic field and hence give a greater deflection for a given speed.

Conclusions.—It is seen that the performance of the magnetic airplane tachometers was not very satisfactory. The average calibration error was about 2½ per cent for full scale reading; the effect of running was 16 per cent and the effect of temperature was 11 per cent. Also the instruments seemed to be of too delicate construction.

COMPARISON OF THE TYPES.

Data showing the performance of the different types of airplane tachometers under various conditions are given in Table XII. The tests are far from being complete; nevertheless a discussion of such results as are given may be of interest.

TABLE XII.—*Airplane tachometer performance—type tests.*

Speed in revolutions per minute.	Error or effect in revolutions per minute.																		
	Calibration error.					Effect of 50° C. temperature change.					Effect of 150 hours running.			Lag error.			Tilting error.		Change at 16,000 feet altitude.
														With vibration.		Without.	Inverted.	On side.	
	Chronometric.	Centrifugal.	Magnetic.	Air viscosity.	Electric.	Chronometric.	Centrifugal.	Magnetic.	Air viscosity.	Electric.	Chronometric.	Centrifugal.	Magnetic.	Centrifugal.	Air viscosity.	Centrifugal.	Centrifugal.	Centrifugal.	Air viscosity.
600	7	23	17	29	22	4	5	64	50	24	6	86	81	10	58	29	52	40	......
800	7	23	19	31	29	4	8	86	60	12	6	81	88	14	30	38	50	42	10
1,000	6	26	20	50	37	5	7	103	83	9	6	92	50	15	26	40	49	41	......
1,200	6	26	27	48	41	5	8	122	94	24	6	82	170	17	13	43	43	36	8
1,400	6	28	22	49	44	6	12	139	111	29	5	73	239	22	11	42	44	35	......
1,600	6	29	26	50	43	6	13	184	126	......	5	67	367	27	13	42	44	31	......
1,800	7	27	42	45	40	6	15	194	135	......	6	61	400	31	19	43	42	33	......
2,000	6	28	37	54	......	7	14	223	155	......	5	58	384	32	18	43	36	27	20
2,200	7	29	44	......	......	8	17	273	......	......	7	62	360	33	25	46	40	27	......
2,400	8	30	54	......	......	9	19	308	......	......	7	64	......	28	......	36	40	24	......

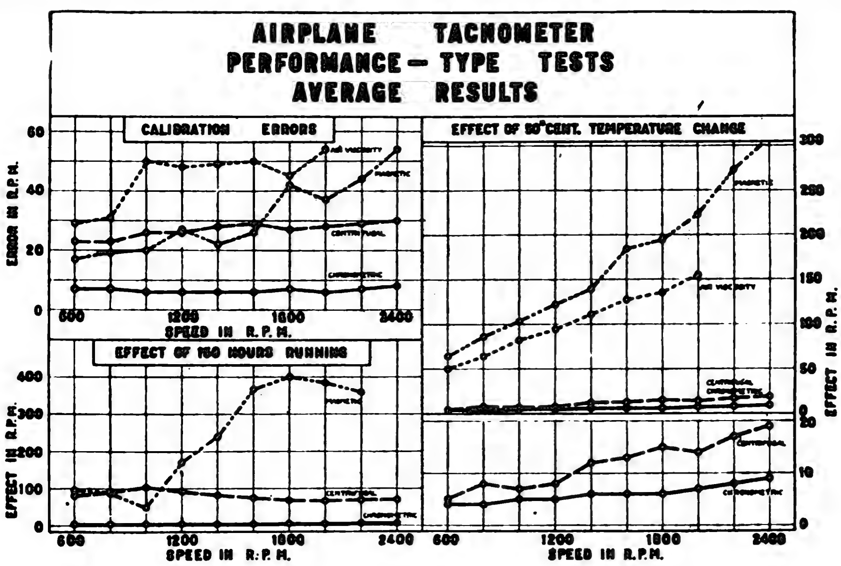


FIG. 13.

The plot, figure 13, shows graphically for comparison (1) the average calibration errors of the chronometric, centrifugal, magnetic, and air viscosity types, (2) the average effect of 150 hours running on the calibration of the chronometric, centrifugal, and magnetic types, and (3) the average effect on the calibration of 50° C. temperature change for the chronometric, centrifugal, magnetic, and air viscosity types. The numerical data for these plots is tabulated in Table XII, mentioned above. The results of the different tests are discussed below.

Calibration.—The type of instrument, number of instruments tested, average calibration error for all speeds in revolutions per minute, average percentage error at speeds of 600 and 2,400, and the percentage of instruments having their average errors in excess of the specification limit of 20 revolutions per minute, are shown below. The percentage error of most instru-

ments is usually less at full scale deflection than at lower speeds, as is evident from the fact that the error in revolutions per minute is more or less constant throughout the scale.

TABLE XIII.

Type.	Number of instruments tested.	Average error. Revolutions per minute.	Average error. Per cent. 600	Average error. Per cent. 2,400	Percentage instruments having average error over 20 revolutions per minute.
Chronometric	204	7	1.2	0.4	7
Centrifugal	73	27	3.8	1.3	63
Magnetic	6	31	2.8	2.3	100
Electric	1	37	3.7	2.2	100
Air viscosity	2	45	4.8	2.7	100

The instruments are arranged in the order of their apparent reliability for calibration. Allowance must be made, however, for the fact that relatively few instruments of the magnetic and air viscosity type and only one of the electric type were tested.

Temperature.—Table XIV is a summary of data showing the average effect in revolutions per minute for all speeds of 50° C. temperature change and in per cent at speeds of 600 and 2,400 revolutions per minute for five types of airplane tachometers. The last column shows the percentage of the instruments tested which had average effects exceeding 20 revolutions per minute.[1]

TABLE XIV.

Type.	Number of instruments tested.	Average effect of 50° C change. Revolutions per minute.	Average effect of 50° C change. Per cent. 600	Average effect of 50° C change. Per cent. 2,400	Percentage instruments having average effect over 20 revolutions per minute.
Chronometric	70	6	0.7	0.4	9
Centrifugal	14	12	.8	1.3	15
Electric	1	20	4.0	2.1	0
Air viscosity	2	101	8.3	7.8	100
Magnetic	5	170	11.0	12.8	100

The instruments are arranged in the order of their apparent reliability for temperature effect.

The performance of the air viscosity and magnetic types for different conditions of tempreature is very poor, so poor, in fact, as to eliminate the types as they exist from further consideration with those suitable for use in airplanes.

Effect of running on calibration.—Table XV is a summary of data showing the average effect at all speeds, of 150 hours running and vibration in revolutions per minute, and in per cent for three types of airplane tachometers. The last column shows the percentage of instruments tested which had average effects exceeding 20 revolutions per minute.[2] The averages for the different speeds are given in Table XII.

[1] Error allowed by Air Service specifications.

[2] Error allowed by Air Service specifications.

TABLE XV.

Type.	Number instruments tested.	Average effect of 150 hours' running.			Percentage instruments having average effect over 20 revolutions per minute.
		Revolutions per minute.	Per cent.		
			600	2,400	
Chronometric	86	6	1.0	0.3	10
Centrifugal	33	73	14.3	2.7	80
Magnetic	1	237	13.5	15.0	100

It is seen that the performance of the centrifugal and magnetic types is very poor as regards consistency of calibration with use.

Lag.—Table XVI shows the average difference in readings for all speeds taken at the same speed with decreasing and increasing speeds. The instruments were vibrated while being tested and had not previously been run. Table XII gives the complete data and also data showing the average lag in the centrifugal type without the vibration.

TABLE XVI.

Type.	Number of instruments tested.	Average lag with vibration.		
		Revolutions per minute.	Per cent.	
			600	2,400
Centrifugal	22	23	1.7	1.2
Air viscosity	2	24	9.7	1.1
Magnetic [1]				
Electric [1]				
Chronometric [2]				

[1] Small; not observed quantitatively. [2] See discussion.

At slow speeds the lag in the air viscosity type is much greater than in the centrifugal. However, if the speed be held constant after being raised or lowered the lag will practically disappear in the air viscosity type while in the centrifugal type it will not. Hence actually the lag effect in the air viscosity type is less serious than in the centrifugal.

Tilting.—The centrifugal type is the only one tested which read differently for different positions of its axis. Data showing the average change at all speeds in the reading at normal or vertical position for two other positions is given in Table XVII and complete data for the different speeds in Table XII.

TABLE XVII.

Type.	Average effect of tilting.					
	In revolutions per minute.		In per cent.			
	Upside down.	On side.	Upside down.		On side.	
			600	2,400	600	2,400
Centrifugal	44	34	8.7	1.7	6.7	1.0
Chronometric [1]						
Magnetic [1]						
Air viscosity [1]						
Electric [2]						

[1] No effect observed. [2] Not tested; believed small.

It is seen that in the centrifugal type the effect of position of the axis of the instrument with respect to the vertical is by no means negligible.

Effect of air-pressure change.—The air viscosity type is the only one of those tested affected by altitude change. Data taken at a barometric pressure corresponding to that at 16,000 feet altitude is given in Table XII.

It is seen that the average effect observed at any speed did not exceed 20 revolutions per minute, the maximum average percentage error being 1.0 per cent.

Durability.—Of the four types, chronometric, centrifugal, magnetic, and air viscosity, the centrifugal type gives the best performance as regards durability. The percentage of breakdowns, complete or partial, so that readings can not easily be taken is small. However, the reading may be considerably different from the true speed as is seen from the foregoing discussion of the characteristics of the type.

About 20 per cent of the instruments of the chronometric type broke down so as to necessitate repairs and replacement of parts. Also, in several cases, the escapement failed to start unless the instrument was shaken. In use on a plane this would necessitate dismantling.

Instruments of the magnetic type did not break down completely, but the pointer gradually became more and more unsteady until finally readings could not be taken.

The air viscosity type was not tested for endurance, but it is believed that its behavior under airplane conditions would be similar to that of the magnetic type.

Weights.—The average weights for the different types are given in Table XVIII.

TABLE XVIII.

Type.	Weight in pounds.
Chronometric	1.3
Centrifugal	1.0
Magnetic	2.0
Air viscosity	1.4
Electric	4.8

Attention is called to the relatively large weight of the electric type.

REPORT No. 129.

POWER-PLANT INSTRUMENTS.

PART III.

THERMOMETERS FOR AIRCRAFT ENGINES.

By E. F. Mueller and R. M. Wilhelm.

SUMMARY.

This part describes the principal types of distance-reading thermometers for aircraft engines, including an explanation of the physical principles involved in the functioning of the instruments and the proper filling of the bulbs. Performance requirements and testing methods are then given, concluding with a discussion of the sources of error and results of tests.

INTRODUCTION.

The term "airplane thermometer" is usually used to designate an instrument, which indicates the temperature of the water or oil at some point in the respective circulating systems of these liquids in an aircraft engine. Thermometers may be used for experimental purposes, to measure tempratures existing in various other regions about the engine or aircraft, but such thermometers will not be discussed in this article.

Thermometers designed for use in the water-cooling system have been used to measure the temperature of the lubricating oil. The use of thermometers for this purpose is not general, although oil thermometers were specified as part of the standard equipment of several types of American airplanes. The discussion which follows will apply more especially to instruments used to measure the temperature of the circulating water.

The bulb of the thermometer is usually placed in the top of the radiator and for this reason these instruments have sometimes been called "radiator" thermometers.

FUNCTIONS.

A temperature indicator for aeronautic engines may serve one or more of the following purposes: To indicate engine trouble, possibly before any of the other instruments would show this; to assist in operating the engine at maximum efficiency; to indicate whether the water is at or near its boiling point, or the oil is at such a temperature that its lubricating properties are impaired; to warn that the engine is becoming too cold to start up again after having been cut off in gliding; to warn that the water is in danger of freezing or that the oil is too thick to flow. The last condition may be encountered in cold climates when the engine is allowed to stand idle for a sufficient period, or on long glides from high altitudes.

REQUIREMENTS.

The requirements for an airplane engine thermometer may be summarized as follows:

1. The indicator must be at a distance from the bulb. This precludes the use of the liquid in glass or other nondistance-reading type of thermometer.

2. The thermometer must indicate temperatures in the range 0° to 100° C. but since the operating temperature of the water in an airplane engine is in the neighborhood of 80° under normal conditions, it is obvious that the instrument should be most reliable over this part of

the scale. Readings in the neighborhood of 0° C. may also be of importance since in long glides or occasionally under other conditions the temperature of the water may be reduced to such an extent that the danger of freezing becomes serious.

3. At high altitude the instrument will be subjected to external pressures much lower than normal atmospheric, and the indications should not be significantly affected by such changes.

4. The gage and connecting tubing may be at various temperatures, since that part of the tubing passing close to the engine may be heated considerably above the other parts of the tubing and gage, while at high altitudes and in winter some parts may be cooled much below the temperature met with at lower altitudes or in summer. The error from this source should be reduced to negligible proportions.

5. The instrument should be light in construction and as small in size as is compatible with strength and visibility. Furthermore, nonferrous materials have been preferred.

POSSIBLE TYPES OF THERMOMETERS.

The types and forms of distance reading thermometers available for practical use may be classified under two general heads; namely, electrical and pressure. A consideration of the relative advantages of these two general types led to the adoption in this country of the pressure instrument for airplanes, on account of smallness in size and weight, ruggedness of construction and immediate availability. This last factor was important since the pressure thermometers on the market could be easily adapted for airplane work, while it would have been necessary to evolve practically a new type of electrical indicator to fulfill the conditions imposed.

A type of electrical thermometer taken from captured German planes consists essentially of a resistance thermometer connected to a small ohmmeter and a battery. It indicates the temperature only at the time when a push button switch is operated.

The advantage of this type of instrument over the pressure thermometers are sensitivity to rapid changes in temperature, absence of errors due to change in atmospheric pressure, or change in temperature of connections. However, its greater complexity, costliness, weight, and inconvenience in that the pilot must operate the push button to observe the reading, offset the advantages above enumerated.

PRESSURE THERMOMETERS.

Pressure thermometers comprise a bulb containing a liquid or gas or both, and connected by means of capillary tubing, to some form of pressure gage.

The pressure thermometers which have been used up to the present time in this country on airplanes are either of the vapor pressure type, with a free surface of the liquid in the bulb, or the liquid filled type, with the liquid completely filling the thermometer.

Two distinct types of gages have also been used, one employing an ordinary Bourdon tube with sector and pinion multiplying mechanism, the other, a long Bourdon tube of many turns which is connected through a bimetallic temperature compensator to the pointer.

Either type of gage could be used for either of these two types of pressure thermometers. The ordinary Bourdon gage, however, has been used up to the present time only for vapor pressure instruments, while the multiple turn Bourdon tube has been used for the liquid filled instruments.

The photograph, figure 1, shows a liquid filled thermometer (A), and two types of vapor pressure thermometers (B and C) used on American airplanes. Interior views of the bulbs and gages of these instruments are also shown.

PRINCIPLES UNDERLYING ACTION OF VAPOR PRESSURE THERMOMETERS.

The action of the vapor pressure thermometer depends upon the fact that the pressure inside the thermometer is determined solely by the temperature of the free surface of the liquid. It follows that the thermometer must be so constructed that one free surface is always in the bulb. If this condition is fulfilled the readings of the instrument will not be sensibly affected by changes in the temperature of the gage and capillary. It must be remembered, however,

that the liquid will always accumulate in the cooler parts if possible, i. e., if these parts are not already filled with liquid (or with noncondensible gas). The two extreme cases to be considered, therefore, are: (1) The bulb is the hottest part of the system. (2) The bulb is the coldest part of the system. The former is the more important and more usual condition. Assuming that the thermometer contains no noncondensible gas, the gage and capillary will fill with liquid and there must still be liquid in the bulb if the thermometer is to indicate properly. It follows that *the volume of liquid must be greater than that of the gage and capillary combined.* An inter-

FIG. 1.—Types of thermometers.
A. Liquid filled thermometer with long Bourdon tube.
B. Methyl-chloride vapor-pressure thermometer.
C. Ethel vapor-pressure thermometer with ordinary Bourdon gage.

esting variation of this case is that in which the volume of liquid is barely sufficient when gage and capillary are at room temperature, but when these are cooled, the liquid in them contracts, so that all the liquid in the system is insufficient to fill the gage and capillary as shown in figure 2 (*a*). The thermometer under such conditions indicates properly when the parts other than the bulb are at room temperature but fails when these are cooled. The second condition, in which the bulb is coldest, may occur occasionally. In this case, the liquid goes to the bulb, but if the volume of liquid is more than sufficient to fill the bulb, the free surface will be in the capillary and the thermometer will fail to indicate properly as shown in figure 2 (*b*). A less extreme case is that in which the capillary or a part of the capillary alone is heated to a higher temperature than either bulb or gage. In this case the liquid will be driven out of the heated parts of the capillary. A thermometer containing more than enough liquid to fill the bulb will fail on the simplest test, namely, it will indicate the temperature of either the capillary or the gage when the bulb is put in ice. It is evident, from the above, that *the volume of the liquid should be insufficient to fill the bulb at any temperature.* From the above two conditions in regard to amount of liquid required it can be seen that *the combined volumes of the capillary and gage must be less than that of the bulb.* It is evident that if a relatively small bulb is required the capillary must be very fine in order that the last-named condition may be fulfilled.

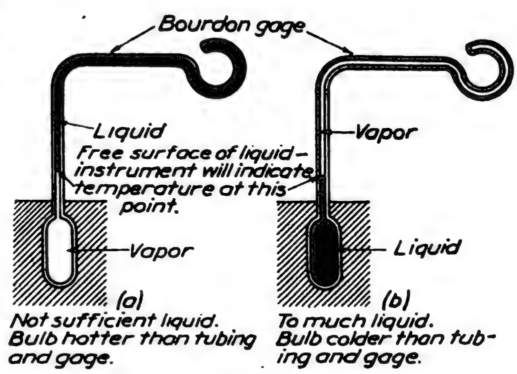


FIG. 2.—Defective vapor pressure thermometers.

The problem of obtaining proper volume relations may be simplified by the use of a transmitting liquid in the tubing and gage. Such a liquid must have a high boiling point, low freezing point, be noncorrosive, and must neither react with nor mix with the volatile liquid. If such a liquid is used to fill the gage and capillary, the effective volume of these is reduced to practically zero, and the necessary volume of the bulb and of the volatile liquid are greatly reduced.

The transmitting liquid type of thermometer has not come into use in this country, although some experimental instruments have been made and submitted for test. The transmitting liquid was a mixture of glycerin and water, the volatile liquid being methyl chloride.

Either ethyl ether or methyl chloride is used as the volatile liquid in the majority of the vapor pressure thermometers in use at the present time on American airplanes. A brief consideration of some of the liquids that could be used may be of interest.

The following table gives the properties of some of the liquids which could be considered for use in a vapor pressure thermometer for an airplane engine, and also the number of degrees centigrade that a thermometer using such a liquid would read high at an altitude of approximately 19,000 feet (one-half atmospheric pressure):

Liquid.	Boiling point.	Vapor pressure at 100° C.	Error at 19,000 feet altitude.	
			Bulb temperature 0° C.	Bulb temperature 80° C.
	° C.	*Atmospheres.*	° C.	° C.
Alcohol (ethyl)	78.3	2.2	62	10
Ether (ethyl)	34.6	6.4	27	5
Sulphur dioxide	−10	27.8	7	1.3
Methyl ether	−24	30 ?	6	1
Methyl chloride	−24	30 ?	5	(1)
Ammonia	−33.4	61	2.5	.5

1 Less than 1° C.

The volatile liquid used must be stable, readily obtained and purified, must not act on the metals with which it will be in contact, must have a sufficiently low freezing point, and its critical temperature must be above 100° C. The table shows that the effects of variations in external atmospheric pressure occurring at different altitudes cause smaller variations in the indications of thermometers filled with liquids having lower boiling points, and consequently higher vapor pressures in the working temperature range. The high-pressure gages used with these liquids are also more robust than the low-pressure gages would be. Methyl chloride, methyl ether, and sulphur dioxide fulfill the requirements as regards physical properties. However, on account of availability and ease in handling the liquid, ethyl ether filled thermometers were the only thermometers of the vapor pressure type produced in quantity up to near the termination of the recent war.

PRINCIPLES UNDERLYING ACTION OF LIQUID-FILLED THERMOMETERS.

The liquid-filled thermometers utilize the thermal expansion of a liquid. The increase of pressure with temperature is nearly linear in the range 0° to 100° C. for the liquids used. Alcohol has been used in these instruments, which are made to have an internal pressure at 0° of about 100 pounds per square inch, the pressure increasing to 700 or 800 pounds at 100° C. This large pressure range requires the use of a rugged gage mechanism and makes the indications of the instrument practically independent of the variations of atmospheric pressure with altitude. Since changes in the temperature of the gage and capillary tubing affect the internal pressure, some form of compensator must be used if these parts contain sufficient volume to make the error from this source appreciable, since they are subjected to considerable changes of temperature in use.

A bimetallic compensating helical coil has been employed. This coil is connected at one end to the pointer spindle and at the other end to the Bourdon tube. It may be designed to compensate for changes in the temperature of the gage alone or of the gage and capillary together. This compensator can not eliminate errors due to changes in the temperature of the capillary alone. It is therefore necessary that the volume of the bulb be large relative to the volume of the capillary.

CHOICE OF TYPE.

Since the vapor pressure of a liquid does not change linearly with changes in temperature but increases much more rapidly at higher temperatures, vapor-pressure thermometers have a very open scale in the upper part of the temperature range and a relatively contracted scale in the lower part of the range. If the upper part of the range is the most important this is an advantage, but there is a corresponding disadvantage if readings in the lower part of the scale are of importance. The liquid-filled type has an equally divided scale.

It has been previously pointed out that vapor-pressure thermometers are subject to error if used at high altitudes and that this error is greater the lower the vapor pressure of the liquid used and the lower on the scale the readings are taken. This error for liquid-filled thermometers may be reduced to almost negligible proportions, and is the same regardless of the part of the scale on which the reading is taken.

It may therefore be said that if it is important that the thermometer shall give accurate indications at lower temperatures, the liquid-filled type is to be preferred.

When correctly filled the readings of the vapor-pressure thermometers are sensibly independent of the temperature of the gage and capillary. The liquid-filled thermometer is subject to error if the temperature of the gage and capillary differs from that at which it was calibrated. This error may in some cases be eliminated by employing a compensator as previously mentioned, but in general it may be said that if the most important consideration were that the indications of the thermometer should be independent of the temperature of the capillary, then the vapor-pressure type should be chosen.

SPECIFICATIONS FOR AND TESTING OF AIRPLANE THERMOMETERS.

The discussion of airplane thermometers which has been given is based on data obtained as the result of a considerable amount of investigation extending over about a year and a half, during which time many tests were made for the military branches of the Government and specifications written in cooperation with the War Department.

These specifications, which were revised from time to time, include, apart from the actual details of construction, a series of tests which were devised for the purpose of inspection.

These tests included primarily determinations of (*a*) the scale errors at various temperatures under ordinary laboratory conditions, (*b*) the error that would be introduced if the tubing or gage either together or separately were heated or cooled to temperatures corresponding to those that might be encountered under actual conditions of use, and (*c*) the error caused by the reduction of the external pressure on the gage, the condition met with at high altitudes.

Other special tests were made from time to time including vibration tests to ascertain the comparative effect of vibration on different instruments, tests to determine the mechanical hysteresis due to poor gage mechanism, the lag in the reading when the temperature was changed quickly, tests to determine whether the indications changed with time or in shipment, and chemical analyses of the liquids taken from the instruments.

APPARATUS USED IN TESTS.

Very little special apparatus was required for these tests, since the thermometry laboratory was already equipped for similar work.

A well-stirred water bath, heated by a bunsen burner, served, with the aid of a standard thermometer, for the determination of the scale errors, the mechanical hysteresis in readings due to faulty gage mechanism, and the lag of the readings.

For cooling the tubing and gage, use was made of a low temperature bath cooled by the expansion of carbon dioxide.

For determining the error caused by the reduction of the external pressure on the gage an ordinary vacuum desiccator evacuated to the required extent was used. The pressures were read on a mercury manometer.

RESULTS OF TESTS.

As a result of the testing, the following conclusions have been reached in regard to the accuracy of the instruments examined and the magnitude of the errors that may be expected under various conditions:

In general it was found that well-made instruments of either the ether vapor-pressure or the liquid-filled types would indicate the temperature of the bulb to within an accuracy of from 1° to 3° C. under ordinary laboratory conditions.

Although methyl chloride and methyl ether vapor-pressure thermometers were produced in quantity toward the end of the war, only a small number were received at the Bureau of Standards for test and some of these were experimental instruments. The results of tests showed that it was possible to construct methyl chloride or methyl ether thermometers possessing an accuracy comparable with that of the liquid-filled types, but in general the readings, especially in the neighborhood of 0° C., were less reliable in the vapor-pressure thermometers.

Mechanical hysteresis errors can be attributed to backlash and friction in the moving parts of the gage mechanism. The advantages of the directly connected gage as used on the liquid-filled thermometer over that of the sector and pinion type, especially if the latter is poorly constructed, was very clearly demonstrated.

The readings of the vapor-pressure type of instrument are theoretically independent of the temperature of the gage and capillary tubing. The heating and cooling tests previously

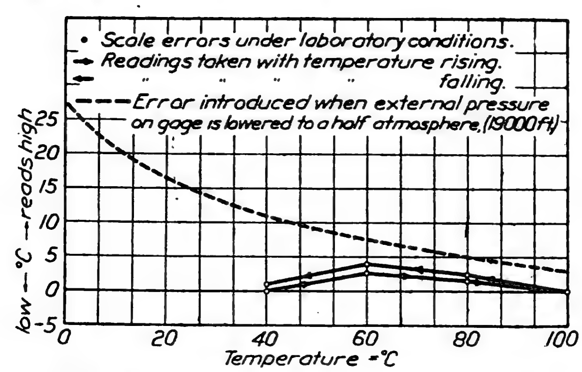


FIG. 3.—Results of tests of ether vapor-pressure thermometers.

mentioned were therefore intended as checks on the filling of the instruments, i. e., to determine whether the proper amount of liquid was contained with reference to the volume of the various parts. Although some of the first thermometers submitted as samples were found not to be properly filled, this defect did not appear in the thermometers furnished under the specifications.

The liquid-filled thermometer is subject to error when the capillary is heated separately from the gage. For lengths up to 12 feet it was found that the capillaries could be made small enough in diameter to permit moderate heating or cooling without introducing excessive error. For longer capillaries the error due to this cause was appreciable, as, for example, a 23-foot tube cooled to −9° C., introduced an error of about 9° C. in the reading. It has been previously stated that a compensator is employed on the liquid-filled thermometers to allow for the expansion or contraction of the liquid in the gage. This compensator may also be so designed as to allow for the expansion and contraction of the liquid in the tubing provided both gage and tubing are heated and cooled at the same time and the same amount. Tests of instruments so designed indicated that it was possible to compensate very accurately for these temperature changes.

The errors caused by decreasing the external pressure on the gage of airplane thermometers depend on the pressure range of the instruments.

The liquid-filled instruments if properly designed will be practically free from error from this source, since the pressure range can be varied at will. Tests of the instruments of the type submitted showed that the error had been reduced to within 1° C. by the use of a suitable gage and sufficient pressure range.

The theoretical errors due to change in external pressure on the gage of vapor pressure instruments have been previously indicated. The errors actually found agreed very closely with those predicted.

Impurities in the liquids used in vapor pressure thermometers may clog up the capillary tubing and render the instruments inoperative. A number of methyl chloride and methyl ether thermometers were found defective from this source. Difficulty in securing pure methyl chloride or methyl ether in sufficient quantities interfered with the manufacture of satisfactory instruments of this type.

Figures 3, 4, and 5 show characteristic calibration curves obtained from observations taken for ether vapor pressure, methyl chloride vapor pressure, and liquid-filled thermometers.

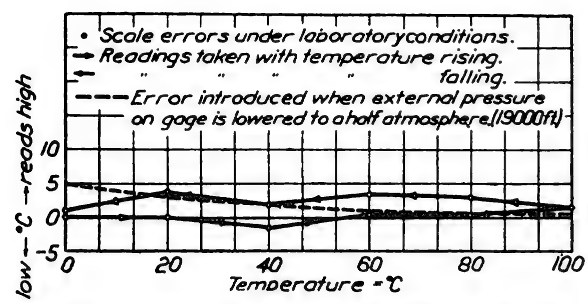


FIG. 4. Results of tests of methyl chloride vapor-pressure thermometer.

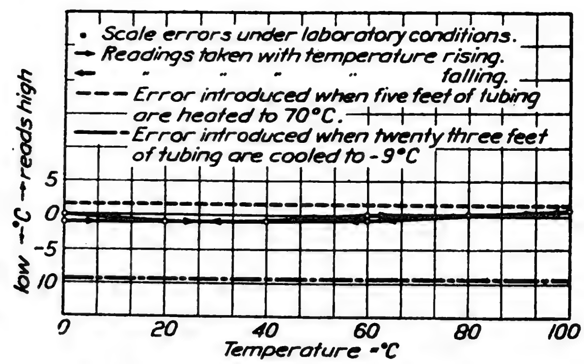


FIG 5.—Results of tests of liquid filled thermometers.

The charts also indicate the magnitude of the error due to reducing the external pressure on the vapor pressure thermometers and to either heating or cooling the capillary of a liquid-filled instrument.

Vibration tests made in the laboratory failed to indicate the superiority of one instrument over the other from the standpoint of ability to withstand hard usage.

Other reasons for failure of the instruments submitted were loose pointers and the breaking of the capillaries. These are frequent causes of failure of the instruments in the field.

It is unfortunate that very little data could be obtained in regard to the behavior of the instruments under actual conditions of use, although it is understood that those passing the tests proved satisfactory.

REPORT No. 129.

POWER PLANT INSTRUMENTS.

PART IV.

AIR PRESSURE AND OIL PRESSURE GAGES.

By H. N. Eaton.

SUMMARY.

This part discusses briefly the use of air and oil pressure gages on aircraft, and describes the construction of various American, British, and German gages. Methods of testing these instruments at the United States Bureau of Standards are described and sample reports are given.

DESCRIPTION OF AIRCRAFT PRESSURE GAGES.

Air and oil pressure gages are used on aircraft to measure the pressure of the air in the gasoline tank and the pressure in the oil system of the engine. The importance of keeping the air pressure in the gasoline tank at the proper value is obvious when it is remembered that it is this pressure which forces the gasoline to the carbureter. The usual pressure is about 3 pounds per square inch, although a value as great as 5 pounds per square inch may sometimes be reached. A safety valve is used to prevent the pressure from increasing beyond this limit. Since the life of the engine depends upon its receiving a sufficient supply of oil, the gage which indicates the oil pressure is also of very great importance. It shows not only whether the pressure is maintained within the proper range but also any stoppage which may prevent the flow of oil.

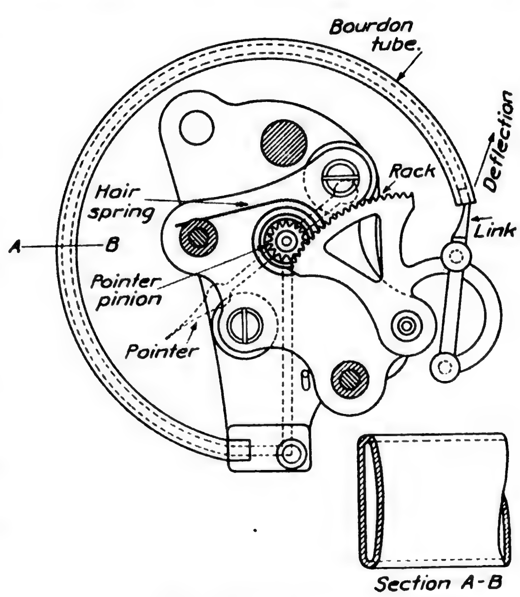


FIG. 1.—Pressure gage.

The pressure gages just mentioned are of the Bourdon tube type in the great majority of cases. A Bourdon tube is constructed by flattening a circular tube, bending the flattened tube longitudinally to the arc of a circle, and sealing the ends. (See fig. 1.) Now if the pressure is introduced into the tube, the cross section tends to increase in area and this change in cross section tends to straighten the tube longitudinally. When a Bourdon tube is used in an instrument, one end is mounted rigidly to the case while the other end is left free to deflect and operate the mechanism. Bourdon tubes possess the advantage that the deflection produced is closely proportional to the pressure applied, but they have very little power when utilized as pressure indicators and so are not adapted to use in instruments where the pressure element is called upon to exert an appreciable force. To change the range of pressure for which the gage is adapted, it is simply necessary to use a Bourdon tube of different stiffness.

Figure 2 shows a group of American, British, and German pressure gages. All of these gages are of the Bourdon tube type except the Prerauer and Scholz gage, figure 2(F), which has a corrugated diaphragm element.

Figure 2(A) shows an American oil-pressure gage whose construction is typical of that used in American aircraft oil and air pressure gages. This gage is of the concentric type; that is, the axis of rotation of the hand is at the center of the dial. A number of American airplane pressure gages have been built with the hand eccentric with respect to the dial, but the mechanism is not materially different from that shown in figure 2(A).

The pressure is applied to the inside of the Bourdon tube through a screw connection under the main casting. The free end of the tube deflects as indicated in figure 1, thus operating the rack through a connecting link. The rack in turn operates the pointer pinion on which the pointer is mounted. A hairspring is attached to the shaft carrying the pointer pinion so as to eliminate the effect of backlash. The Bourdon tube is usually made of seamless drawn bronze.

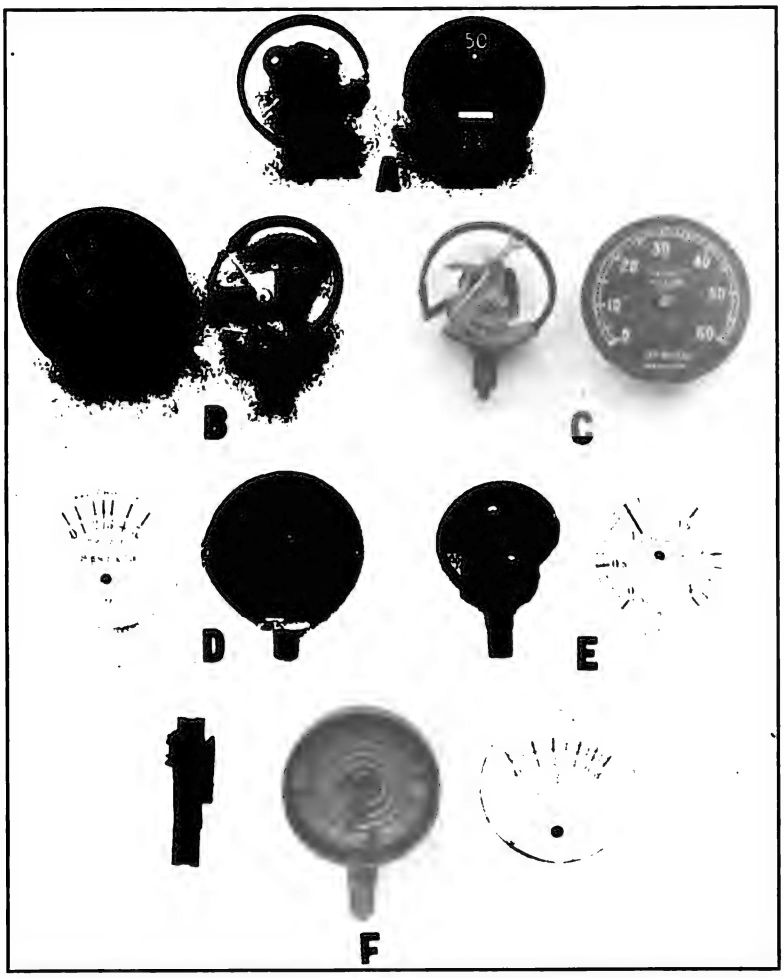


Fig. 2.

The graduations on the dial of this particular instrument are not luminous, but it is customary to have the pointer and the principal graduations and figures finished with luminous paint.

A British air-pressure gage is shown in figure 2(B). In this instrument the hand is mounted eccentrically with respect to the dial. Owing to the small angular motion required of the pointer, the rack and pinion are replaced by a linkage which is simpler to construct and will give practically a uniform scale. Stops are arranged for the zero position and for preventing the Bourdon tube from deflecting so far as to overstrain the metal in case of an accidental application of overpressure. The tube is made of seamless phosphor bronze tubing. Neither the pointer nor the graduations on the dial are luminous. A conspicuous red line is printed at the point of the scale corresponding to 2.5 pounds per square inch indicating the proper pressure to be maintained.

Figure 2(C) shows a British oil-pressure gage with a range of 0 to 60 pounds per square inch. A rack and pinion are used to transmit the motion of the free end of the Bourdon tube to the pointer. No hairspring is used to eliminate backlash, but instead the teeth are made V shaped, so that there is practically no lost motion between the rack and the pinion. No stop is provided to prevent the Bourdon tube from being deflected too far. The specifications, however, require this gage to sustain a total pressure of 180 pounds per square inch without damage; consequently the stop is hardly needed.

Figure 2(D) shows a Benz air-pressure gage of German manufacture having a range of from 0 to 5 pounds per square inch. Here, as in the British air-pressure gage, only a small angular motion of the pointer is utilized, and a linkage is used to transmit the motion of the free end of the Bourdon to the pointer.

A German oil-pressure gage is shown in figure 2(E). The instrument has a range of from 0 to 4 kilograms per square centimeter (approximately 0 to 57 pounds per square inch). A rack and pinion are used and a hairspring eliminates backlash in the mechanism. A stop curved to fit the outer surface of the Bourdon tube is mounted on the case. If the Bourdon tube is subjected to overpressure, it comes in contact with this stop for a considerable portion of its length and so overstrain of the metal comprising the thin walls of the tube is prevented.

Figure 2(F) shows a German air-pressure gage of the diaphragm type. As the diaphragm deflects it raises with it a helical surface shown above the diaphragm in the figure. The pointer is mounted on a shaft which carries an arm with a small wheel to provide rolling contact with the helical surface. Consequently, as the surface rises it rotates the arm and the pointer shaft. A hairspring takes up backlash. Owing to the fact that the relation between the applied pressure and the deflection of the diaphragm is not linear, this instrument has a scale whose graduations are far from uniform.

TESTS OF AIRCRAFT PRESSURE GAGES.

The tests to which airplane pressure gages are subjected are designed to bring out clearly any characteristics of an instrument which would make it unsuitable for use under the conditions peculiar to aeronautics. In particular, the gages must work satisfactorily under severe vibration and at low temperatures. The tests specified are as follows:

1. Calibration.
2. Vibration.
3. Temperature.
4. Friction.
5. Endurance.
6. Interchangeability.

CALIBRATION TEST.

When the gages are received they are calibrated at room temperature in order that their scale errors under normal laboratory conditions may be ascertained. The air-pressure gages are calibrated directly against a mercury column, since the range of the instruments (usually 0 to 10 pounds per square inch) is sufficiently small to permit the use of this method. Air pressure is applied sufficient to deflect the pointer to the 2-pound division while the instrument is tapped, and the true pressure is read on the manometer which is graduated in pounds per square inch. This process is repeated for successive 2-pound intervals over the scale, first with increasing pressure, then immediately afterwards with decreasing pressure. The difference in the manometer readings with increasing and with decreasing pressure is a measure of the elastic hysteresis of the instrument (if backlash and friction are eliminated).

Since oil-pressure gages have a much greater range than the air gages, usually from 0 to 120 pounds per square inch, it is not convenient to use a mercury column as the standard for meassuring the pressures. Instead a dead weight oil gage tester is used. This tester consists of a vertical cylinder in which a piston of known cross-sectional area floats on oil. An oil-filled tube connects this cylinder with the gage under test. Weights can be placed upon the piston, and since the cross-sectional area of the latter is known, the pressure thus set up in the oil system is

also known for any given weight. For purposes of testing, the weights are designed to alter the oil pressure as they are applied by successive increments of 5, 10, or 20 pounds per square inch.

The calibration of the oil gages is carried out just as described for the air gages. Readings are taken for pressure changes of 20 pounds per square inch over the range of the instrument with both increasing and decreasing pressure.

VIBRATION TEST.

This test is made to determine the effect of prolonged vibration upon the instrument, such as may occur under flight conditions. The result may be simply to change the calibration of the instrument slightly or to loosen parts of the mechanism.

After the calibration test just described has been completed, the gages are fastened rigidly to a vibrating stand and for five hours are subjected to vibration similar to that experienced in actual service. At the end of this time they are recalibrated. A comparison of the two calibrations, one before, the other after, vibration, serves to determine any change produced by this treatment, and a brief examination of the instrument suffices to detect any looseness which may have been produced in the mechanism.

TEMPERATURE TEST.

The effect of temperature changes upon the calibration of each type of gage is determined by tests at approximately $-10°$ C and $+40°$ C. For this purpose the gages are mounted in a chamber in which the temperature can be varied over the necessary range. The air in the chamber is brought to the desired temperature and maintained at that point until the gages have acquired the temperature of the air. The calibration is then made in a manner similar to that already described.

FRICTION TEST.

Pressure is applied sufficient to deflect the pointer over a small portion of its range and a reading is taken without tapping the instrument. The instrument is then tapped and a second reading is taken while the pressure is held constant. The difference in the two readings is a measure of the friction at this point of the scale. The process is repeated at several other points of the scale. The average change in reading due to tapping the instrument is taken as the friction error. Friction is rarely serious in pressure gages, as the vibration of the airplane tends to eliminate its effect. An instrument is not often rejected because of friction unless there is some defect of the mechanism which causes the pointer to stick and move in a jerky manner when the pressure is varied uniformly.

ENDURANCE TESTS.

Three distinct endurance tests are given airplane pressure gages at the Bureau of Standards:

(a) A *drift* test to determine the effect of prolonged application of pressure.

(b) A *seasoning* test to determine the effect of repeated applications of pressure.

(c) An *overpressure* test.

(a) *Drift.*—The increase in reading of an instrument when subjected to a given pressure for a prolonged period is called its "drift" or "creep." This effect is due to the yielding under stress of the metal which makes up the pressure element. The gage is subjected for five hours to sufficient pressure to produce approximately one-half of full scale deflection. A reading is taken when the pressure is first applied and another at the end of the five-hour interval. The difference in the two readings is taken as the drift.

(b) *Seasoning.*—A calibration is given immediately after 200 applications of pressure sufficient to produce full-scale deflection have been given the gage. A comparison of this calibration with the room temperature calibration following the five-hour vibration of the instrument shows the effect of repetition of pressure.

(c) *Overpressure.*—In order to test the ability of the gages to withstand the occasional accidental excess pressures which may be given them, both types of gage are subjected to a momentary overpressure. After the application of this overpressure, the gages are rested for

a few minutes so that the worst of the temporary elastic effect caused by the overpressure may disappear; then a final calibration is given. Since the overpressure often causes a permanent change in the calibration of the gage, this final calibration should be taken as characteristic of the instrument at the conclusion of the tests. In the overpressure test a pressure of 25 pounds per square inch is applied to air gages of 10-pound range, while a pressure of 180 pounds per square inch is applied to oil gages of 120-pound range.

It is desirable to rest the instruments for several hours between each two consecutive tests in order to afford time for the disappearance of the temporary elastic effects produced by the last test.

INTERCHANGEABILITY TEST.

Since both the air and oil pressure gages used by the Air Service are of the same size and general construction, certain parts can be made standard for all. Consequently it is required that cases, connections, bezels, and cover glasses shall be interchangeable. On this account the dimensions of such parts are checked at the conclusion of the performance tests of the instruments.

TOLERANCES FOR AIRCRAFT PRESSURE GAGES.

The following table summarizes the tolerances specified for aircraft oil and air pressure gages used by the United States Air Service. The values are in pounds per square inch.

Table of tolerances for aircraft pressure gages.

Gage.	Range.	Vibration.	Scale error −10° C to +40° C.	Friction.	Drift.	Over-pressure (amount).
	Pounds per square inch.					
Air	0–6	0.3	0.3	0.3	0.3	15
Do.	0–10	0.3	0.3	0.3	0.3	25
Oil	0–120	3.0	3.0	3.0	3.0	180

The following are typical reports for two American pressure gages, one air and one oil.

REPORT ON AIR PRESSURE GAGE, SERIAL NO. 156.

Range of instrument, 0 to 10 pounds per square inch.

The results of the tests applied to this instrument follow. Corrections are in pounds per square inch and are to be added algebraically to the instrument reading.

Instrument reading.	Corrections at +25° C.		Corrections at +25° C.		Corrections at −8.5° C.		Corrections at +46° C.	
	Before vibration.		After vibration.		Cold run.		Hot run.	
	Up.	Down.	Up.	Down.	Up.	Down.	Up.	Down.
Pounds per square inch.								
2	+0.1	0.0	+0.1	0.0	+0.1	+0.1	0.0	0.0
4	+0.1	+0.1	+0.1	+0.1	+0.1	+0.2	+0.1	0.0
6	0.0	−0.1	0.0	0.0	+0.1	+0.1	0.0	−0.1
8	0.0	0.0	0.0	−0.1	+0.2	0.0	−0.1	−0.2
10	0.0	....	+0.1	....	+0.1	....	−0.1	....

Change in reading due to—	Average.
	Pounds per square inch.
Vibration	0.0
High temperature	+0.05
Low temperature	−0.10
Repetition	0.0
Drift (at 5 pounds per square inch)	0.1
Overpressure	....

REPORT ON OIL PRESSURE GAGE, SERIAL NO. 157.

Range of instrument, 0 to 120 pounds per square inch.

The results of tests applied to this instrument are as follows:

Instrument reading.	Corrections at +25° C. Before vibration.		Corrections at +25° C. After vibration.		Corrections at −6° C. Cold run.		Corrections at +42° C. Hot run.	
	Up.	Down.	Up.	Down.	Up.	Down.	Up.	Down.
Pounds per square inch.								
20	+2.0	0.0	+1.5	0.0	+3.0	0.0	+1.5	0.0
40	−1.0	−2.0	0.0	−1.5	0.0	−1.0	−0.5	−2.5
60	0.0	−3.0	−1.0	−2.5	0.0	−1.5	−1.5	−2.5
80	0.0	−2.0	−0.5	−1.5	0.0	0.0	−1.5	−2.5
100	+1.0	0.0	+0.5	0.0	+2.0	+1.5	−0.5	−1.5
120	+3.0	....	+2.5	....	+4.0	....	+0.5	....

Change in reading due to—	Average.
	Pounds per square inch.
Vibration	+0.05
High temperature	+0.75
Low temperature	−0.95
Repetition	+0.05
Drift (at 60 pounds per square inch)	0.5
Overpressure	+0.2

REPORT No. 129.

POWER PLANT INSTRUMENTS.

PART V.

GASOLINE DEPTH GAGES AND FLOWMETERS FOR AIRCRAFT.

By John A. C. Warner.

GASOLINE DEPTH GAGES.

The development of a satisfactory gage for indicating the depth of fuel in the reservoirs of aircraft has received much attention from instrument designers both in America and in foreign countries. As yet, however, their efforts have not met with unqualified success owing to the unfavorable conditions under which these instruments function.

Such an instrument must be so designed as to be compact in form, light in weight, easily attached to the tank and removed therefrom, and so mounted as to be accessible to the pilot. Furthermore, it is desirable that the instrument be easily adaptable to tanks of different depths, and that the system allow for mounting the indicating gage at a distance from the tank; this latter feature is necessary in cases where the reservoir is at some distance from the pilot. The ideal instrument should be as simple as is consistent with good operation characteristics; it should have as few working parts as possible, and should function properly under the varying conditions of vibration, temperature, pressure, etc., which are encountered in service.

It is the object of this paper to consider the principal types now in use, to make a general summary of the advantages and disadvantages of each type, and to outline the methods employed in their testing and calibration.

FLOAT TYPE.

Several of the most common and most satisfactory gages incorporate the float principle in their construction (see figs. 1 and 2). In general, this type has the advantage of simplicity of construction and operation, while its greatest disadvantages are found in the tendency of moving parts to stick, and in the structural difficulties which ordinarily result in a more or less cumbersome arrangement not easily adapted to satisfactory installation on aircraft. In spite of the disadvantages, however, the instruments of the float type present a promising basis for the future development of depth gages.

Float-and-swinging-rod gage.—Figures 1 (A) and 2 (A) show assembled and disassembled a gage which combines the float with a swinging rod and suitable indicating head to show the fuel depth. Three vertical stationary rods extend from the base of the indicating head to a stay-plate to which they are rigidly attached at their lower extremities near the bottom of the tank. A fourth rod with a rigid angle-arm at either end is free to swing about a center pin mounted on the stay-plate and fitting loosely through a hole in the extremity of the lower angle-arm. The upper angle-arm attaches at the lower extremity of a vertical indicator spindle extending upward through a protective housing to the indicating head.

The two halves of the split cylindrical shellacked cork float, seen in its lowest position in figure 1 (A), are held apart by an aluminum spacer so as to admit one of the stationary vertical rods at one side of the slotted opening, and the swinging rod at the other. These rods are held in a definite position relative to the float by small guide rollers which also provide a bearing with little friction as the float rises and falls with changes in gasoline level. The float and rods are

so designed and mounted that the free rod is caused to swing in a definite path as the float changes its position. This motion is transmitted through the upper angle-arm to the indicator spindle above mentioned.

At the upper end of this spindle is a toothed sector, figure 2 (A), which engages a pinion mounted upon the vertical center axle of a cylindrical rotating scale, the divisions of which are marked upon the curved surface of the cylinder. A cylindrical glass ring with a diameter slightly larger than that of the rotating scale surrounds the latter and provides an observation window at one side where a section of the indicator housing is cut away.

Inasmuch as this instrument is adapted to use on tanks under pressure it is necessary that the glass ring be mounted upon a gasket which rests upon the inner base surface of the indicator housing. A screw top, also provided with a cork gasket resting upon the upper surface of the glass, caps the indicator and makes it air-tight. An air-tight connection is likewise made at the joint between tank and gage by means of a fitting mounted on the tank and threaded to accommodate a ring-clamp, shown in the illustration. A cork gasket serves to make the joint free from leaks.

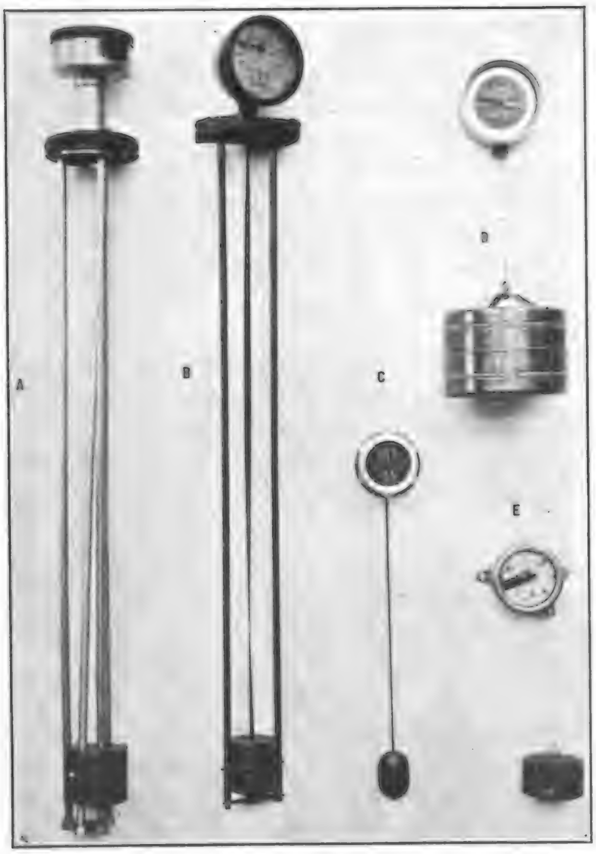


FIG. 1.—Float Type Gas line Depth Gages—Assembled.

This type of gage generally operates in a reasonably satisfactory manner when properly mounted and handled, and is widely used. However, inasmuch as a very small component of the buoyant force of the float is effectively used in causing the rod to swing, there is great possibility of sticking, with resulting incorrect indications. This type also has the disadvantage of being more or less cumbersome and not well adapted to distant indication.

Float twisted-strip gage.—An older type of gage than the one described above is shown assembled and disassembled by figures 1 (B) and 2 (B). The hollow metal float is seen at its extreme lower position. Two vertical guide rods extending from indicator base to stay-plate at the bottom of the tank restrict the float motion to a vertical path as the float-guide pulleys rest upon the rods. A spiral twisted metal strip passes through a slotted opening through the center of the float so that as the latter moves along its vertical path, the twisted strip is caused to turn like a loose fitting screw of very long pitch in the corresponding nut.

The rotation of the strip which extends upward into the indicator housing is there transmitted through a pair of bevel gears to the indicating pointer. The cover-glass is held in place by a bezel ring. This joint is made air-tight by means of a cork gasket.

The advantages and disadvantages of this gage are practically the same as those of the swinging-rod instrument. The frictional difficulties are usually greater in this type.

Float-and-lever gage.—The float-and-lever type of gage as illustrated assembled and disassembled by figures 1 (C) and 2 (C) is little used on American airplanes. However, it deserves a brief description.

The float composed of balsa wood is attached at the end of a wire lever which extends directly to the gage head, where it is bent at right angle to pass through a brass sleeve which screws into the back of the case. The indicating device with which this instrument is equipped

is one of the simplest. As is clearly shown in figure 2 (C) the float lever carries a magnetized steel bar at the indicator end. This bar rotates with changes of float position and acts magnetically upon the steel pointer through a thin air-tight separating wall cast integral with the case. The scale of the instrument shown is graduated to give indications of the last 20 gallons in the tank only. The pointer is centered on the dial by means of a pivot point centrally mounted thereon. A cover-glass held by a bezel ring covers the gage.

It is seen that this type of indicator has the advantage of simplicity, and because of the absence of the necessarily air-tight joint usually found between glass and case is freer from the possibility of leakage. The case is threaded so as to be easily mounted upon a brass tank-fitting shown in the illustration. This gage has the disadvantage of being adapted to comparatively few installations and does not lend itself well to the requirements of distant indication.

Float-and-cord gage. One of the simplest float gages is that which consists of a cork or sheet metal float, usually in the form of an air-and-water-tight cylindrical or spherical chamber, connected to an indicator by means of a light braided silk cord in such a manner as to give indications

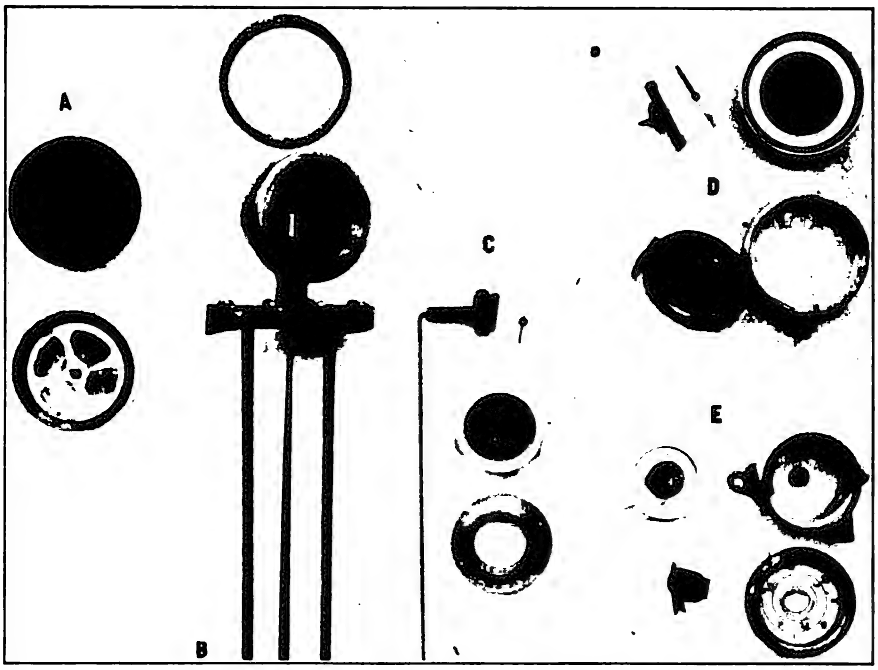


FIG. 2.—Float Type Gasoline Depth Gages Disassembled.

of the depth of fuel in the tank. Figures 1 (D) and 2 (D) illustrate an instrument of this type recently designed by the Engineering Division, United States Air Service.

The cylindrical brass float has a diameter of 134 millimeters, a depth of 93 millimeters, and weighs approximately 600 grams. When installed on the tank this float is restricted in its motion to a vertical path by means of a fixed sheet metal tube of diameter slightly greater than that of the float and reaching from the top of the tank to a point near the bottom. A braided silk cord connects the float with the indicator gage, and the design is such that the gage may be mounted at a distance from the tank. In this case the cord passes through a tube of small diameter with suitable roller fittings at the bends.

At the point of entrance into the case of the gage the cord passes over a roller and thence to the main pulley member, upon which it is wound by the action of a coiled flat metal spring. The motion of this pulley is transmitted to the magnetized pointer bar (see illustration) through a train of gears which are interchangeable so as to make the gage readily adaptable to tanks of different depths. The first set of gears provides a pointer movement of 330° for a 50-inch change in float level, while the second combination gives a pointer movement

of 120° for a 10-inch change of level. The pointer is acted upon magnetically through the dial plate by the magnetized pointer bar mentioned above and moves over the scale marked upon the dial plate as the pointer bar changes its angular position. The case is covered by a glass held in place by a suitable bezel ring, making a tight joint with the case.

A float-and-cord gage of German manufacture is pictured in figures 1 (E) and 2 (E). The cylindrical metal float member has a diameter of 67 millimeters, a depth of 44 millimeters, and weighs approximately 92 grams. As in the design above described this float moves in a vertical path within a guide tube whose diameter is slightly greater than that of the float, and in a similar way connects by means of a cord with the main pulley member of the indicator.

The pointer is attached to a bronze rack (see fig. 2 (E)), which is mounted on the face of the rotating pulley, so as to engage a pinion fixed to the end of the pulley bearing. The rack is free to move radially. When the pulley is rotated by the cord attached to the float, the rack is rotated with it and forced outward radially by the fixed pinion, thereby causing the end of the pointer, which is attached to the rack, to describe a spiral path on the dial. In this way the pointer may make several revolutions without confusing the readings.

Float-resistance gage.—Several of the foreign gages, such as the French Electro-Jauge, depend upon electrical means to show the position of the float in the tank. The float is held in the usual manner by guide rods. An additional vertical column parallel to the guide rods and passing through the cork float has a bare wire resistance winding along its entire length; contact with this resistance element is made by a brush mounted on the float.

As the float changes its position with changes in gasoline level, the amount of resistance cut into the circuit by the float contact varies. A galvanometer, properly graduated and mounted upon the instrument board, shows the pilot the amount of fuel in the reservoir by giving an indication of the current flow through the resistance in the circuit of which the galvanometer forms a part.

This type of gage is well adapted to remote indication. It is too complicated in construction, however, does not hold its adjustment well, and is likely to get out of order.

PRESSURE TYPE.

Gasoline depth gages of the pressure type involve the use of a totally different principle from that of the float type described above. (See figs. 3 and 4.) The principle upon which this design is based is that of the pressure difference between the top and bottom of the gasoline reservoir caused by the head of gasoline. In general, this type is well adapted to distant reading, and the indicator is usually mounted on the instrument board at some distance from the reservoir to which it is connected by means of metal tubing of small bore.

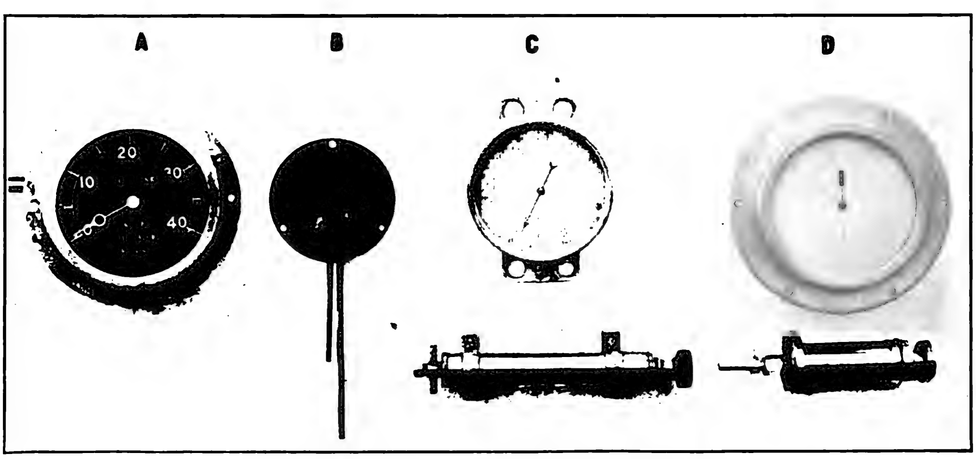


FIG. 3.—Pressure Type Gasoline Depth Gages—Assembled.

This arrangement possesses the disadvantage of being more liable to leakage, and consequent hazard to the aircraft and passengers, a particularly important point with fighting machines, when the tubes are in constant danger of breakage from gunfire.

Aneroid gage.—Figures 3 (A) and (B), 4 (A) and (B) show views of assembled and disassembled American gasoline depth gages of the pressure type which depend on a stack of nine aneroid chambers for pressure indications. Two metal tubes of small diameter lead from the gasoline reservoir to the indicator. One of these tubes extends into the tank to within about one-quarter of an inch of the bottom, while the second tube simply connects to the top of the reservoir above the surface of the liquid. The former then transmits a pressure, equivalent to the air pressure above the gasoline plus that due to the head of gasoline, to the space surrounding the aneroid chambers in the air-tight indicator case to which it is connected. The latter tube transmits the air pressure only to the space inside the aneroid boxes with which it communicates. Thus it will be seen that the elastic aneroid system will assume its position corresponding to the differential pressure existing between the top and bottom of the reservoir—i. e., a pressure equal to that of the hydrostatic head of gasoline.

Two wire coils soldered to the edges of the aneroid chambers at one side prevent that side from moving when pressure is applied, so that the expansion is taken up by a tilting action of

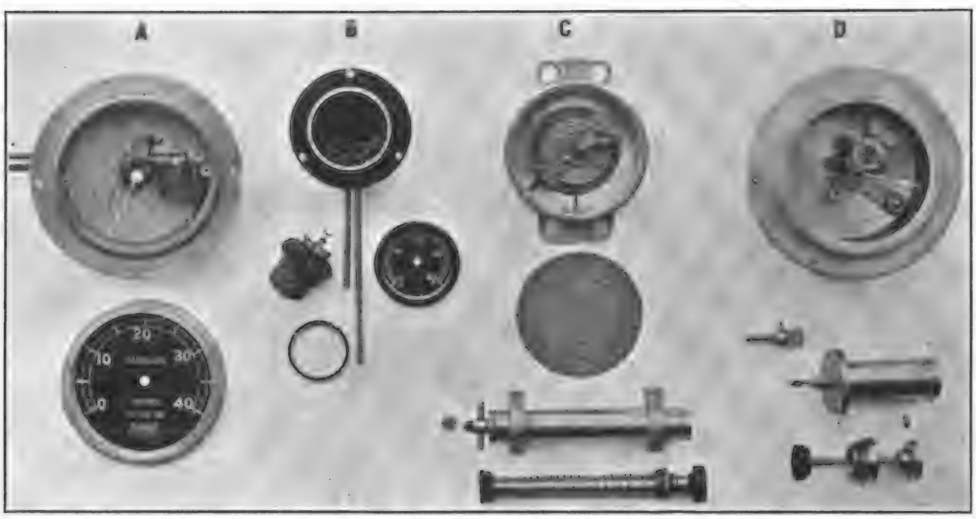


FIG. 4.—Pressure Type Gasoline Depth Gages—Disassembled.

the stack. This motion of the aneroids is preferable to the straight expansion, such as would take place without the restraining wires; for by the tilting action the connecting lever is given a proper motion which it transmits, through a link, to a toothed sector. The sector in turn transmits the motion to the pinion mounted on the pointer arbor. A flat spiral spring holds the pointer in equilibrium and takes up the backlash.

Figures 3 (C) and 4 (C), 3 (D) and 4 (D) show two foreign types of gasoline depth gage for use on reservoirs which are not under pressure. A small hand pump connected to a tube extending from the indicator to the bottom of the fuel reservoir serves to supply enough air to equalize the pressure due to the head of gasoline in the tank. When the pump is operated so as to supply a pressure equal to that of the head of gasoline, bubbles of air are formed at the lower end of the tube and rise to the surface of the liquid. This equalizing pressure is transmitted through a tube to the indicator which is properly graduated to show the depth of fuel in the tank.

The French instrument shown with its pump assembled and disassembled in figures 3 (C) and 4 (C) uses a single aneroid chamber for the pressure element. The action of this type is similar to that described above and will be readily understood after examination of the illustration.

The British type of indicator shown assembled and disassembled in figures 3 (D) and 4 (D) uses, as its pressure element, a specially treated fabric diaphragm approximately 90 mm. in diameter. The air pressure from the hand pump exerts a force upon one side of this diaphragm, which then becomes distended. The resulting motion of the diaphragm is greater or smaller according as the necessary equilizing pressure for the head of gasoline is large or small. A rod supported at the center of the diaphragm transmits its motion to the indicating mechanism which needs no detailed explanation.

As mentioned above, instruments of the pressure type lend themselves readily to remote indication. They are, however, subject to various errors due to several causes, chief among them being leakage, friction, temperature changes, vibration, imperfect elastic properties of pressure element.

TESTING OF GASOLINE DEPTH GAGES.

Tests of float type gages.—Gages of the float type are tested in the laboratory to determine their calibration and operation characteristics, by properly mounting them on a gasoline tank equipped with a water-glass type of gage and provided with means for rapidly filling and emptying.

A careful preliminary inspection of the gage will usually disclose any important causes for poor operation, such as bent parts, etc. The gage which appears to be in good working condition, is first mounted on the tank and a calibration is made by comparing its indications with those of the tank gage as the gasoline level is changed. This is first done with a rising liquid surface and then with a descending surface. Differences in the two readings are usually due to lost motion in the mechanism and should not be excessive. Readings should be taken both with and without tapping so as to determine the frictional error. In case the float or other part sticks so badly that slight jarring will not move it, the instrument should be readjusted before final calibration.

It is sometimes advisable to conduct rough tests of the tightness of metal floats and also of the buoyancy of cork floats, although any difficulties of the kind would usually be noticed in the calibration tests. In making tests of a new type of gasoline depth gage it is advisable to investigate, in addition to the above characteristics, its behavior in flight or in a perturbed liquid.

Tests of pressure type gages.—The apparatus required for the testing of pressure type gages consists of a simple liquid manometer of large bore with suitable scale and with connections and valves to control the air pressure from a source of supply. The scale may be divided to read directly in inches of gasoline, or by the use of gasoline or liquid of equal specific gravity in the manometer the unmodified inch graduations may be used. In testing, the gage is connected with the manometer and the source of air supply. Various pressures are then applied and comparative indications of gage and manometer noted.

The temperature tests are conducted in a thermally insulated chamber equipped with heating and refrigerating coils by means of which the temperature may be varied as desired. Vibration tests are made by mounting the instruments upon a board which is caused to vibrate by an electric motor mounted thereon and with an unbalanced weight upon its shaft. By varying the motor speed the frequency of vibration may be changed and brought to approximately that which the instrument would experience when installed on aircraft. Additional tests which require no explanation will be noted in the report below. This specimen report will afford an understanding of the various tests, and the results will give a notion as to the performance of gages of the aneroid type.

REPORT ON TWO ANEROID TYPE GASOLINE DEPTH GAGES.

Calibration test.—The two gages were calibrated at 22°C, −3°C, +50°C, and also at room temperature before and after being subjected to vibration, repeated stress, and over pressure. In each case the pressures corresponding to a series of scale readings were determined, with increasing pressures to full scale deflection and immediately afterwards with decreasing pressure back to zero.

Numerical results, additive corrections computed for gasoline of specific gravity 0.68, are given in the following tables and the accompanying graphs:

INSTRUMENT No. 13.

Observed reading, inches of gasoline.	Correction at 22° C., reading—		Correction at −3° C., reading—		Correction at 50° C., reading—	
	Up (1).	Down (2).	Up (3).	Down (4).	Up (5).	Down (6).
0......	−1.2	−1.2	−0.8	−1.2	+0.1	−0.5
5......	−0.4	−0.5	−0.3	−0.4	+0.7	−0.2
10......	−0.4	−0.5	−0.1	+0.5	+0.8	−0.2
15......	−0.2	−0.5	0	+0.4	+0.5	−0.6
20......	+0.2	−0.3	+0.5	+1.1	+0.6	−0.1
25......	+0.5	+0.1	+0.6	+1.3	+0.6	−0.3
30......	+0.1	+1.1	+0.5	+1.2	+0.4	−0.5
35......	+0.3	+0.4	+0.4	+1.4	−0.2	−0.5
40......	0	0	+0.7	+0.7	−0.5	−0.5

INSTRUMENT No. 14.

Observed reading, inches of gasoline.	Correction at 22° C., reading—		Correction at −3° C., reading—		Correction at 50° C., reading—	
	Up (1).	Down (2).	Up (3).	Down (4).	Up (5).	Down (6).
0......	−0.6	−0.5	−0.8	−0.3	−0.1	−0.2
5......	−0.1	−0.4	−0.1	−0.2	+0.8	+0.1
10......	+0.3	+0.1	+0.8	+0.4	+1.1	+0.4
15......	+0.7	+0.6	+0.5	+0.9	+0.9	+0.1
20......	+0.9	+0.6	+0.7	+1.1	+0.8	+0.1
25......	+0.8	+0.4	+0.6	+0.9	+0.6	−0.1
30......	+1.0	+0.7	+0.7	+1.4	+0.4	−0.4
35......	+0.4	+0.2	+0.4	+1.4	−0.1	−0.4
40......	−0.7	−0.7	+0.8	+0.8	−0.2	−0.2

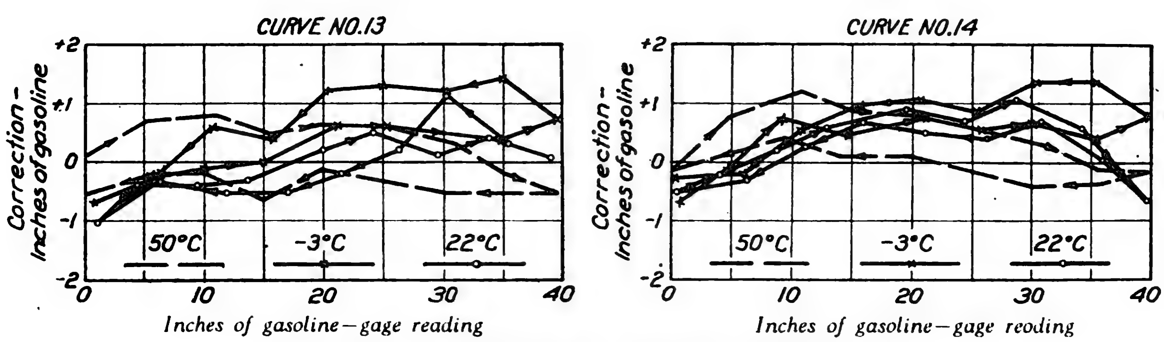


FIG. 5. –Calibration curves for aneroid gasoline depth gages. Temperature tests.

Friction test.—Readings taken with and without tapping with the dials of the instruments vertical showed the following differences:

Instrument Nos.	Differences, inches of gasoline.
13...........................	0.0 to 0.7
14...........................	0.0 to 0.6

Both gages were slightly irregular in action, but not sufficiently so to warrant rejection.

Inclination test.—The differences of readings taken with the dials first horizontal and then vertical for a series of pressures up to full scale deflection were as follows:

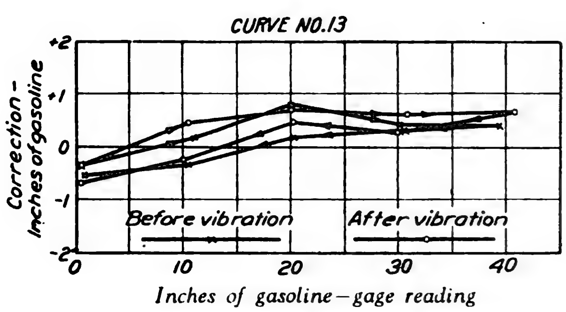
Instrument Nos.	Differences, inches of gasoline.
13	0.2 to 0.9
14	0.0 to 0.8

Drift and fatigue test.—The error caused by the elastic fatigue of the diaphragms under continuous pressure was determined by maintaining the instruments at a constant pressure equivalent to a scale reading of 20 for five and one-half hours. The drift or increase in readings at this pressure was as follows:

Instrument Nos.	Drift, inches of gasoline.
13	+0.9
14	+0.9

After subjection to 500 successive applications of a pressure equivalent to half scale deflection, the calibration varied from previous values by not more than 0.7 inch of gasoline in any case. Instrument No. 14 showed after this test an increase in the error of approximately 0.2 inch of gasoline throughout the scale.

Effect of vibration.—The effect of vibration was determined by calibrating the instruments before and after vibration for 18 hours on a machine which simulated the vibrations experienced in an airplane in flight. In general, a slight increase in the errors which reached a maximum of 0.9 inch of gasoline was obtained (see plots). The pointer of No. 13 vibrated excessively—from four to five divisions.



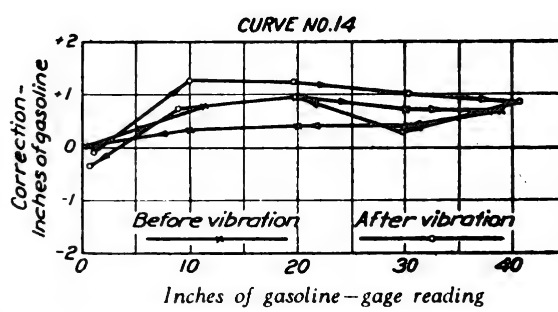


FIG. 6. Calibration curves for aneroid gasoline depth gages. Vibration tests. (Room temperature.)

Excess pressure test.—The calibrations of the instruments before and after subjection to a momentary pressure of twice the maximum scale value differed in no case by more than 0.4 inch of gasoline.

FLOWMETERS.

In connection with performance tests of aircraft engines it is necessary that the rate of fuel flow be ascertained. It is also often desirable that similar indications be available to the aviator during long flights. Several types of instruments have been designed for this purpose and the following description refers briefly to two typical ones.

SCHROEDER FLOWMETER. (ECONOMETER.)

The instrument shown assembled and disassembled at the right of figs. 7 and 8 is the flowmeter developed by Maj. R. W. Schroeder, of the United States Air Service. The base casting is designed so that the inlet pipe from the fuel reservoir connects directly to the vertical meter tube threaded into the base and held concentrically within a surrounding tube of glass. The latter is firmly held in place upon a cork nonleak gasket seat in the base casting by means of a screw cap threaded at the top of the meter tube and extending over the glass. The cap is also provided with a gasket to make the joint free from leaks. A small adjustable screw threaded centrally into the cap and with hollow shank connecting with the atmosphere through a small radial hole is provided at the top for venting the meter.

The inner vertical tube to which the feed line is connected has an inside diameter of approximately 9½ millimeters and a narrow longitudinal flow-controlling slit cut at one side to allow the entering liquid to flow from it into the annular space included between the inner and outer tubes. From this annular space the gasoline passes through the exit opening in the base and thence to the motor.

FIG 7.—Flowmeters—Assembled.

A light brass plunger fitting loosely in the central tube has mounted upon it an index pointer extending through the slit and moving over a vertical scale as the flow varies. This scale is fastened to the front flat milled surface of the tube. When the meter is in action the gasoline flowing into the main tube exerts a force upon the lower surface of the plunger sufficient to overcome its weight and thus lifts it to a definite position in the tube. The height to which it rises depends directly upon the rate of flow.

The instrument shown in the illustration weighs 575 grams and has an over-all height of approximately 160 millimeters. The glass tube has an internal diameter of approximately 26 millimeters.

R. A. E. MARK II FLOWMETER.

The instrument shown assembled and disassembled at the left of figures 7 and 8 is the flowmeter developed by the Royal Aircraft Establishment, of Farnborough, England. It is of the vane type and gives indications of rate of flow between the limits of 5 and 30 gallons per hour. Its action may be described as follows:

The gasoline from the fuel reservoir enters the meter case through a two-way valve which may be turned so as to by-pass the gasoline when, for any reason such as breakage of the meter, this procedure becomes desirable. Referring to the detail illustration at the left of figure 8 a fixed guide or baffle plate is seen projecting from the circumference of the case to the center. The gasoline enters the meter through an opening directly at the right of this guide plate and leaves it through an exit opening directly at the left of the guide. In passing from the entrance to the exit side the gasoline impinges upon the surface of a movable vane mounted upon the central pointer spindle. Sufficient clearance is left between the vane and the surrounding parts to allow the liquid to pass, but in so doing it exerts sufficient force upon the vane to move it through a certain angle, the magnitude of which depends upon the amount of flow. A helical coiled spring holds the pointer with the required force against the action of flow.

Inasmuch as the displacement of the vane does not bear a linear relation to the rate of flow when a leakage space of constant area is left around the vane, it is necessary to provide means for compensating for this characteristic. This is effected by having the space between the side wall and the end of the vane vary in depth, thus varying the leakage area at the vane extremity. When the pointer is at its minimum indication the vane occupies a position directly opposite the entrance opening. At this position the space between the wall and the end of the vane is

smallest. From this position it increases uniformly to a point opposite the exit opening, thus giving the instrument a uniform scale. The cover-glass is held in place by a bezel ring, which clamps it tightly against a nonleakable gasket joint at the case rim.

The vane described above has a length from center to end of approximately 36 millimeters and a depth of 13½ millimeters. The wall surrounding the vane has a maximum height of 15 millimeters, an inside diameter of 74 millimeters and an outside diameter of 80 millimeters. The case has an outside diameter of 90 millimeters and depth of approximately 34 millimeters. The instrument complete weighs about 1 kilogram.

FIG. 8. Flowmeters Disassembled.

An older form of flowmeter designed and used in Great Britain consisted of a suitably mounted vertical glass tube through which the gasoline flowed. The tube was ground internally so that the inner surface was conical and with the smaller end at the bottom. A phosphor-bronze ball within the tube assumed a position of equilibrium at a height where the rate of flow through the annular space between the ball and the walls of the tube was such that the upward force on the ball was equal to the weight of the latter in gasoline. The scale fitted beside the glass tube was graduated experimentally to show the different rates of flow. A by-pass valve was provided so that the gasoline could be diverted from the tube in case of breakage.

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